Joint workshop “GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOaccess”

May 31st – June 4th, 2021

Considerations for Double-Crystal setups at the LHC

A. Fomin, D. Mirarchi, S. Redaelli

Acknowledgements: A. Mereghetti

Outline

Introduction

- LHC collimation system
- Crystal collimation at the LHC

Double crystal setups at the LHC

- General idea
- Two proposed layouts: at IR8 (LHCb) and at IR3

Considerations for layout at LHCb

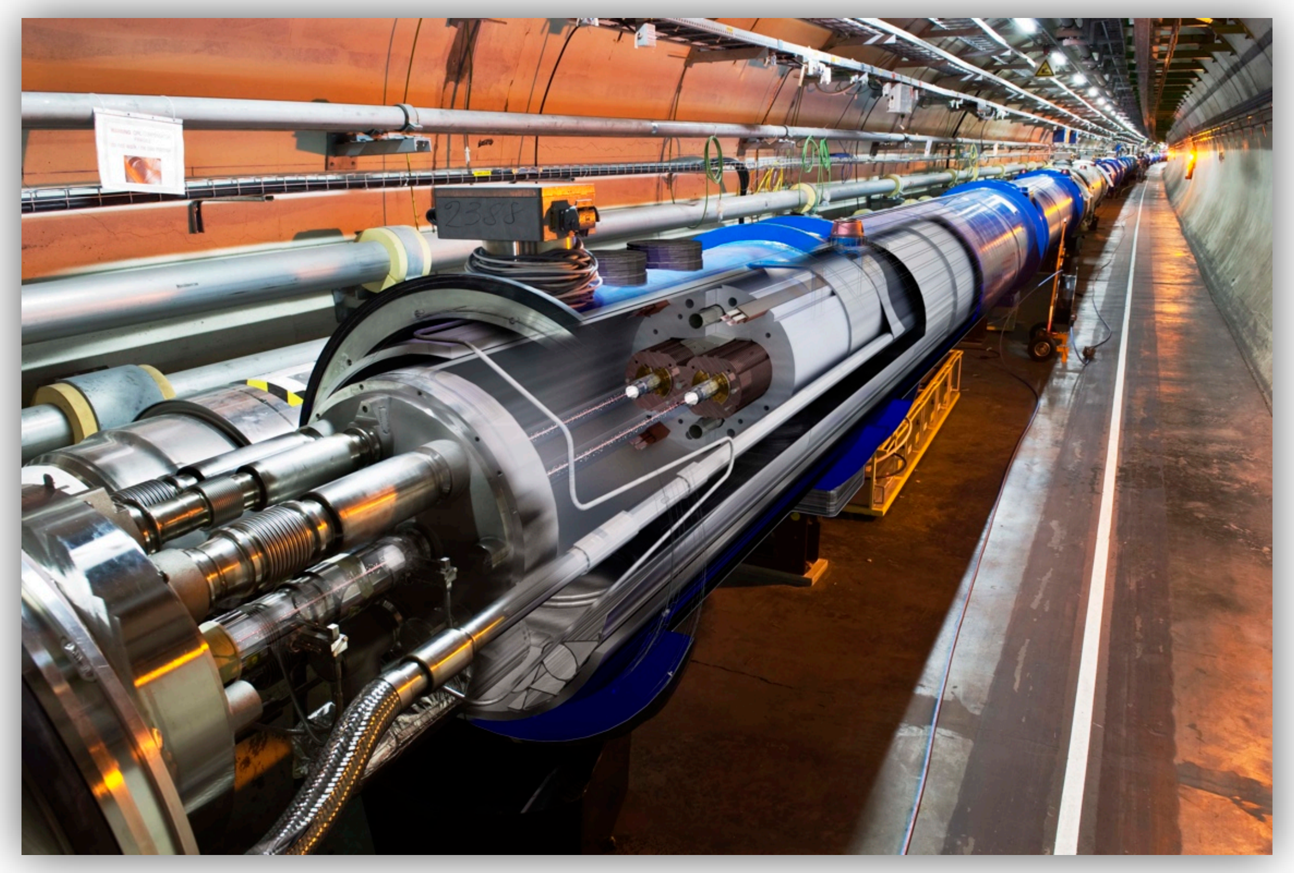
- Beam and channeled halo displacements during levelling
- Channeled halo and new VELO aperture

Possible improvements of double crystal setups efficiency

- Longer target
- Alternative layout (IR8→IR3)

Introduction

Introduction: LHC collimation

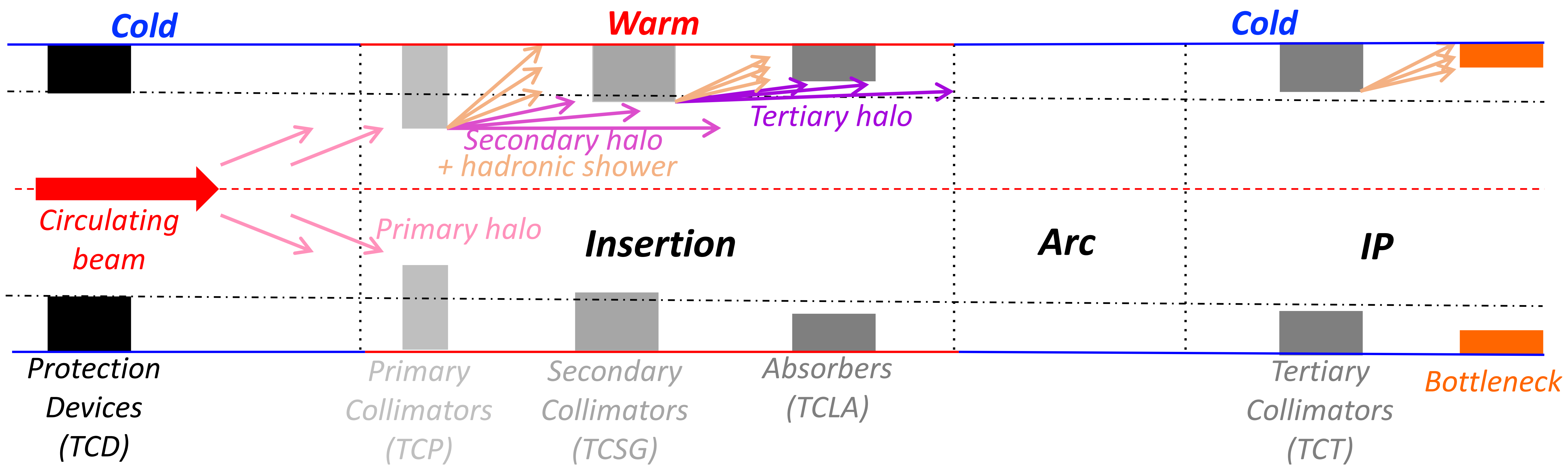


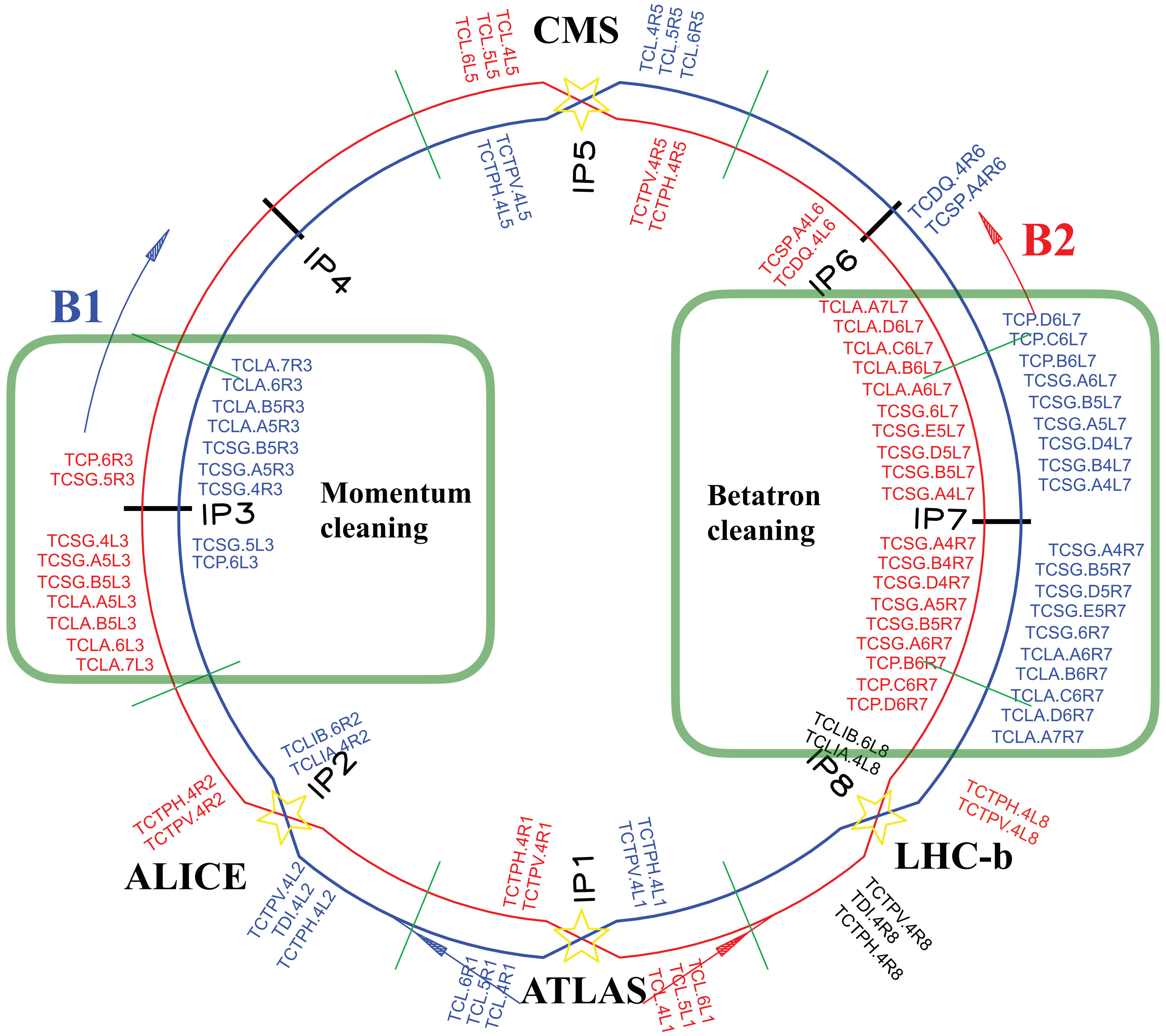
The LHC: biggest and most powerful particle accelerator ever built

- stored energy: **360 MJ** (LHC design) → **700 MJ** (HL-LHC)
- quench limit: **15—50 mJ/cm^3**
  - → Highly efficient collimation system needed for a safe beam disposal at any time

LHC Collimation system

- multi-stage cleaning: **TCP** → **TCSG** → **TCLA** + **TCT** + **TCDQ**
- 50 collimators per beam
- two dedicated insertions at **IP3** and **IP7**





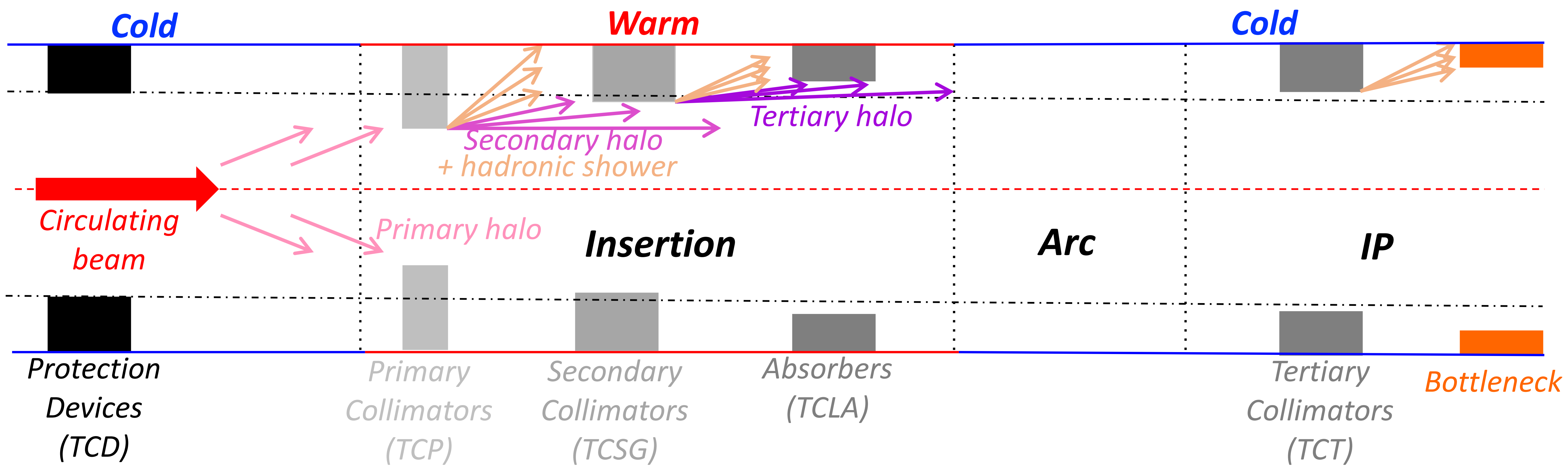
Introduction: crystal collimation at the LHC

Crystal-based betratron halo cleaning (concept)

- Bent crystal replaces horizontal and vertical primary collimators
- A single massive absorber (per plane) intercepts the channeled halo
- Needs additional shower absorbers, but “cleaner” disposal of primary losses

Challenges:

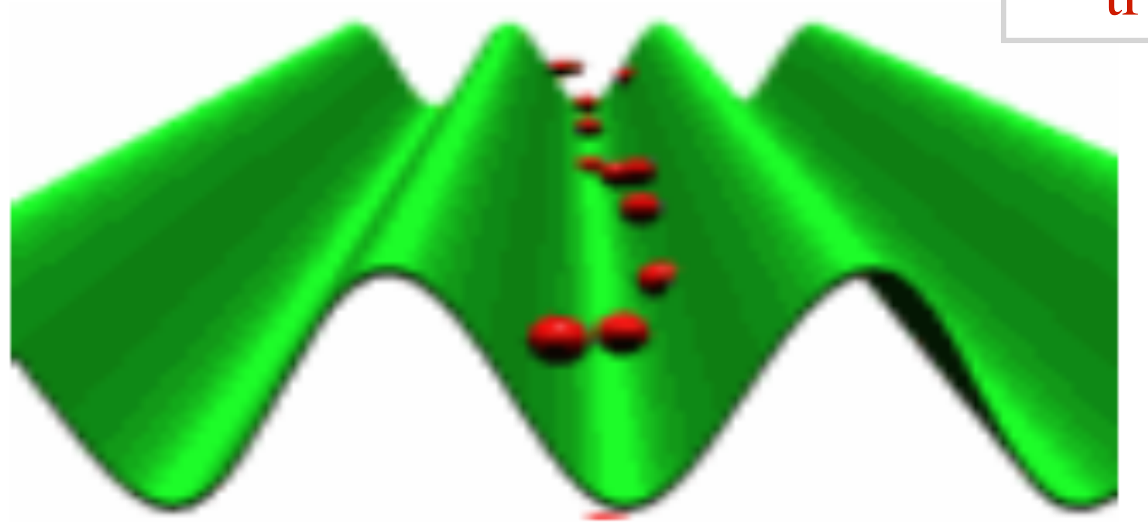
- Quality and performance of crystal assembly (new energy regime)
- Angular control within sub-micro radiants
- Safe and efficient disposal of channeled halo



Planar channeling

$\varepsilon_{tr} < U_{pl}$

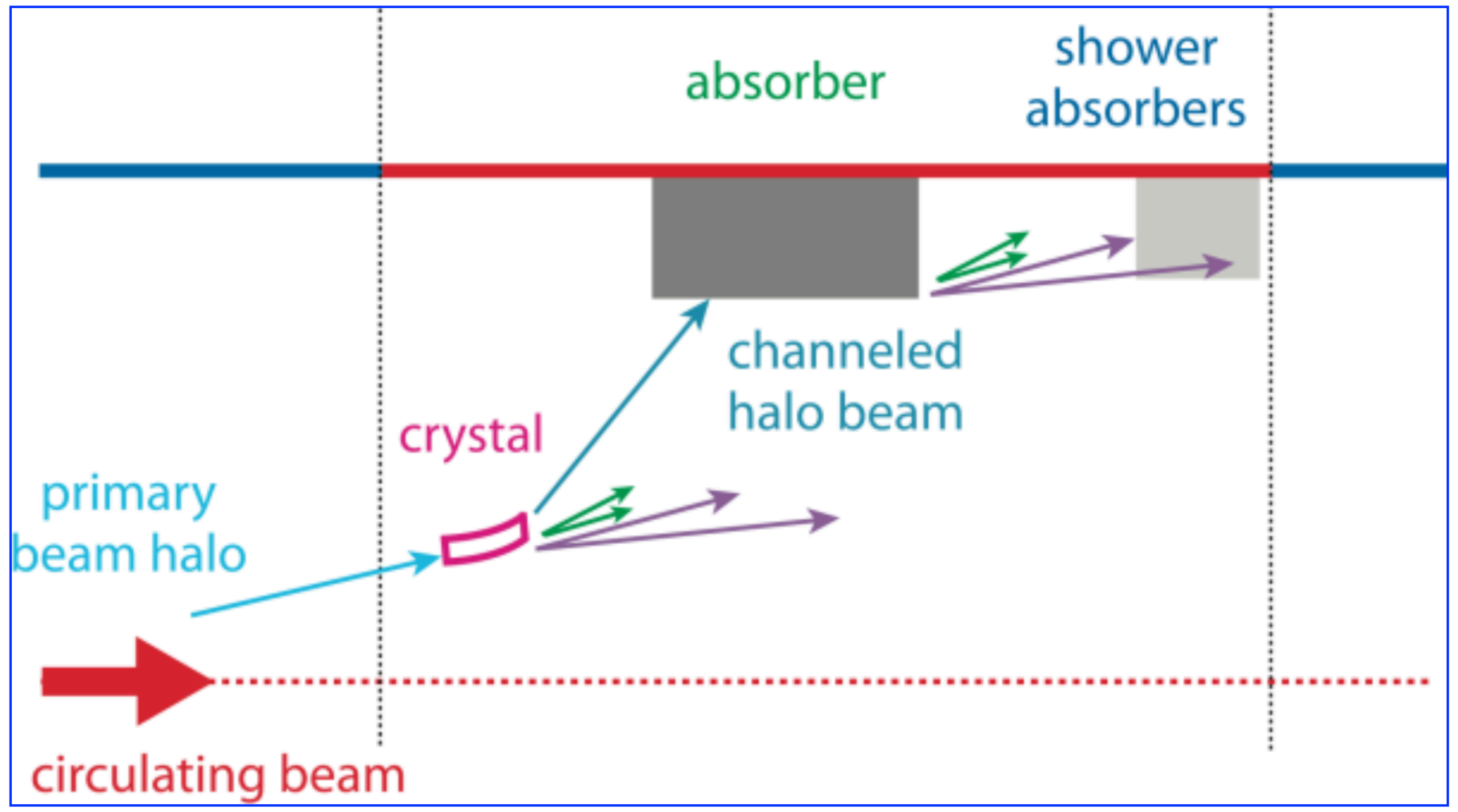
$\theta_L = \sqrt{\frac{U_{pl}}{2\,\varepsilon_{tr}}}$



Potential of crystallographic planes

Equivalent magnetic field for 50μrad at 7 TeV proton beams: 310 T (4 mm crystal)

Replace the 3-stage system for betatron cleaning



Improvement of cleaning, with fewer collimators, in particular for heavy ion beams

Introduction: crystal collimation at the LHC

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LHC beam tests: key milestones

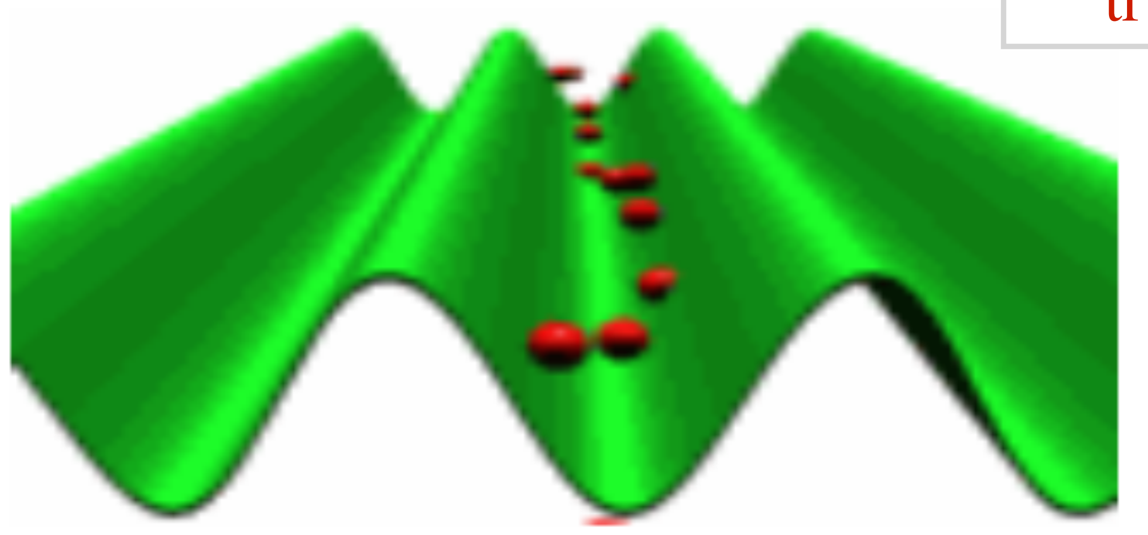
- 2015: first observation of channeling at the LHC: 450 GeV and 6.5 TeV
- 2016: Continuous channeling during energy ramp
- 2016: First assessment of cleaning performance with p beams
- 2018: operational tests with 6.37 Z TeV Pb beams with high intensity

➡ Decision to include crystal collimation as part of the HL-LHC upgrade baseline

Planar channeling

$\varepsilon_{tr} < U_{pl}$

$\theta_L = \sqrt{\frac{U_{pl}}{2\,\varepsilon_{tr}}}$



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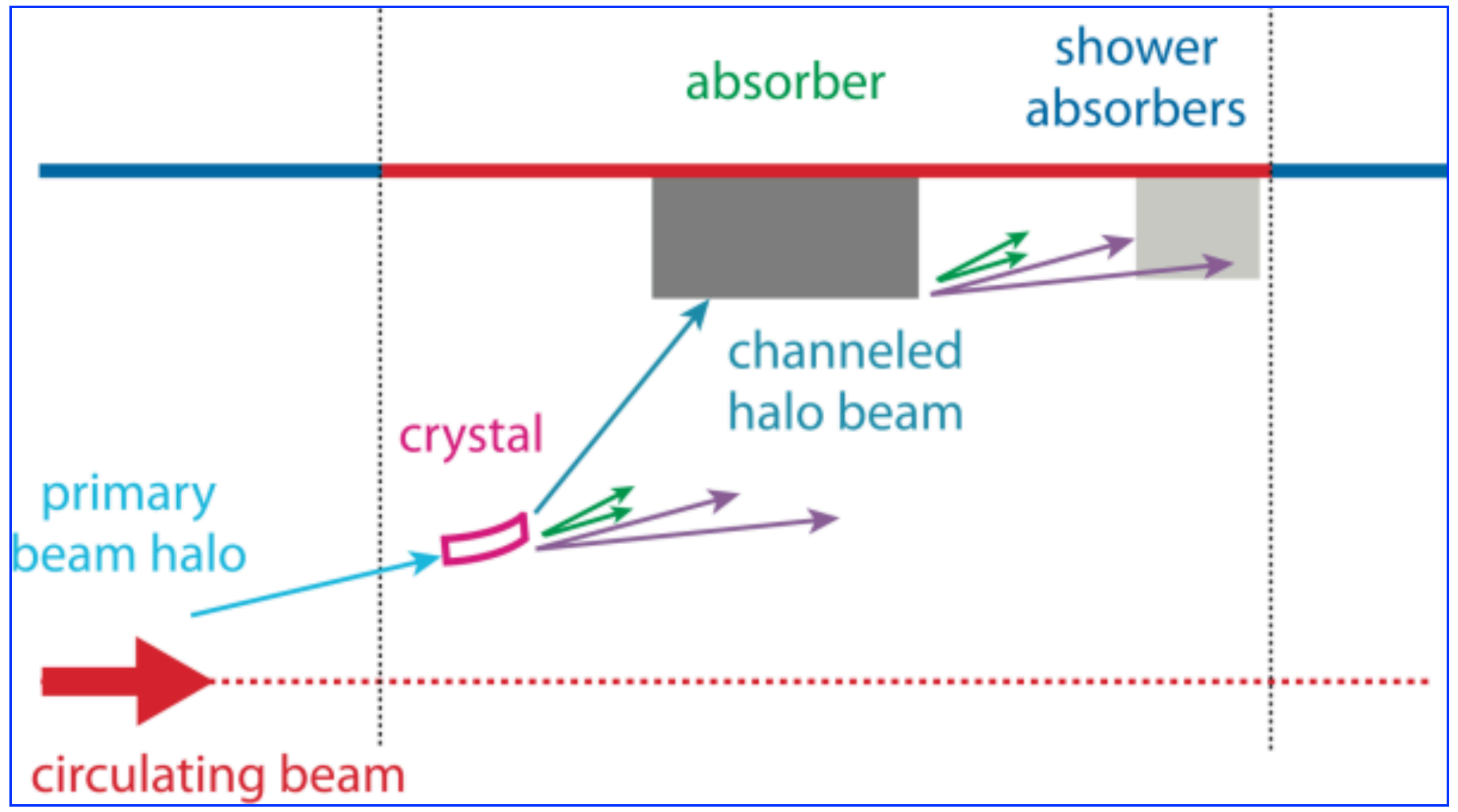
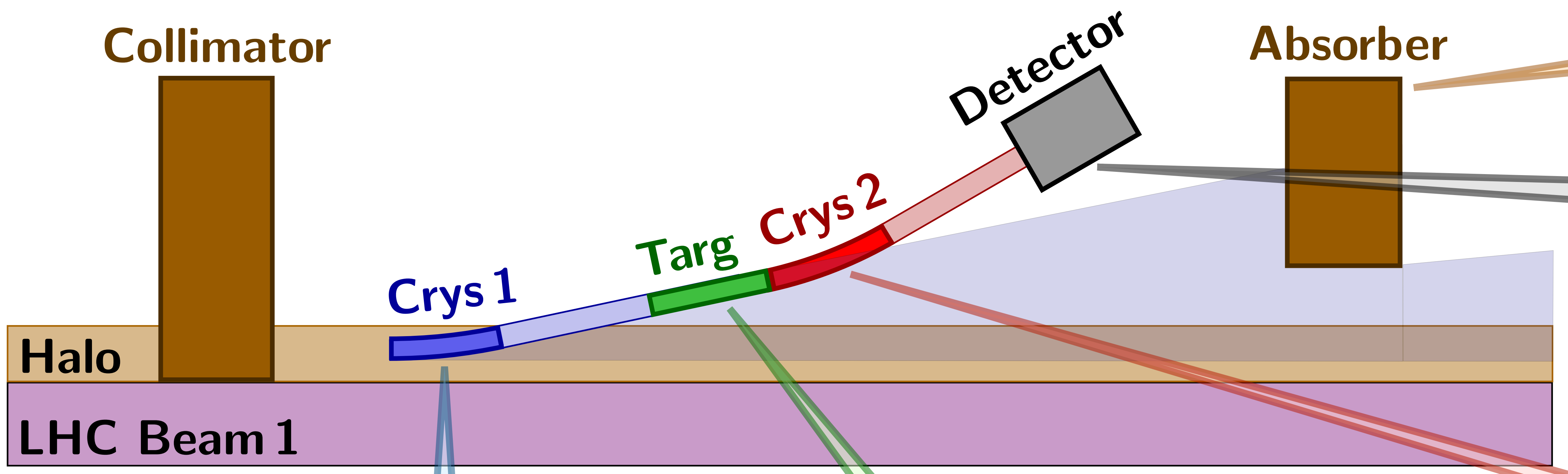


Improvement of cleaning, with fewer collimators, in particular for heavy ion beams

Double crystal setups at the LHC

Double crystal setup at the LHC



Beam halo particles that do not interact with the Target+Crys2 assembly are intercepted by 4 double-sided LHC-type collimators

In the Detector the final polarisation of Λc is reconstructed from the distribution of decay products

The first Crystal deflects protons from the LHC beam halo onto the Target

In the Target protons are converted to polarised Λc

The second Crystal deflects Λc with specific initial polarisation.

Λc spin precession in the electric field of crystal planes is proportional to MDM (or EDM)

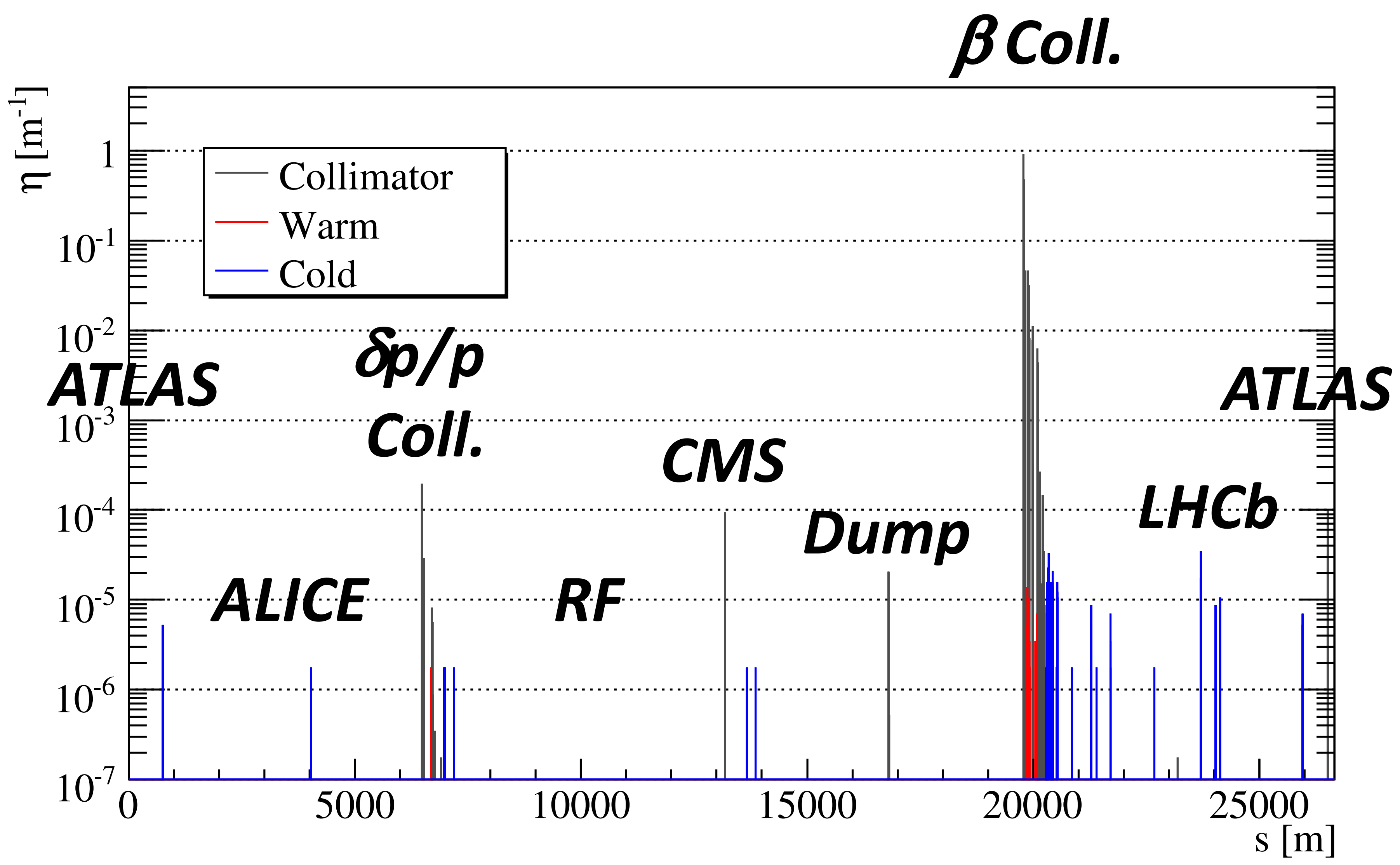
Starting point: Presented at the PBC kickoff: Sep. 2016
(Mirarchi, Redaelli, Scandale, Stocchi)
indico.cern.ch/event/523655/

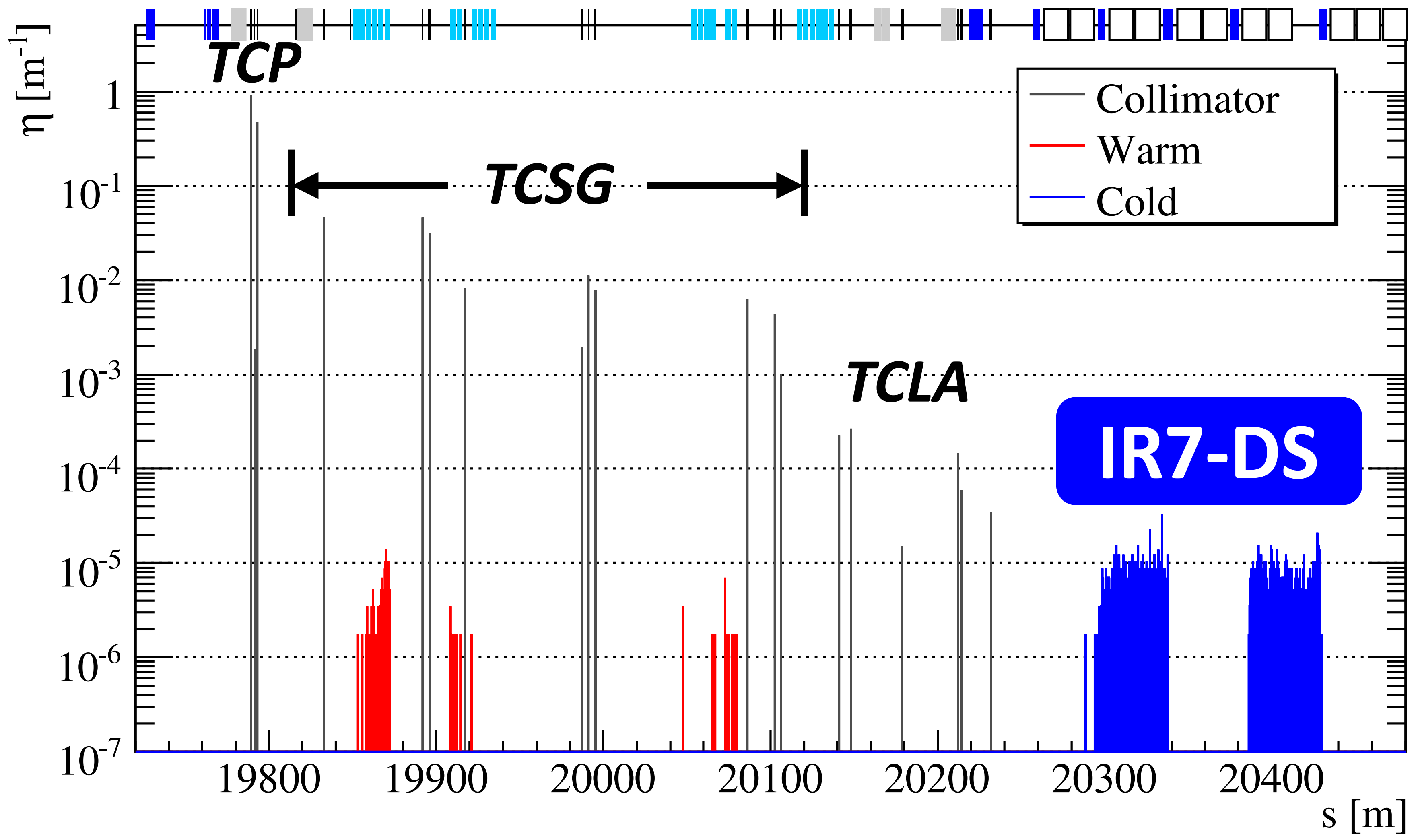
Recent publications on the layout:
- D. Mirarchi et al., Eur. Phys. J. C 80, 929 (2020)
- PBC-FT WG report: CERN-PBC-REPORT-2019-001

Double crystal setup at the LHC: Operational scenario definition

D. Mirarchi, FTE @ LHC & NLOAccess STRONG 2020 joint kick-off meeting

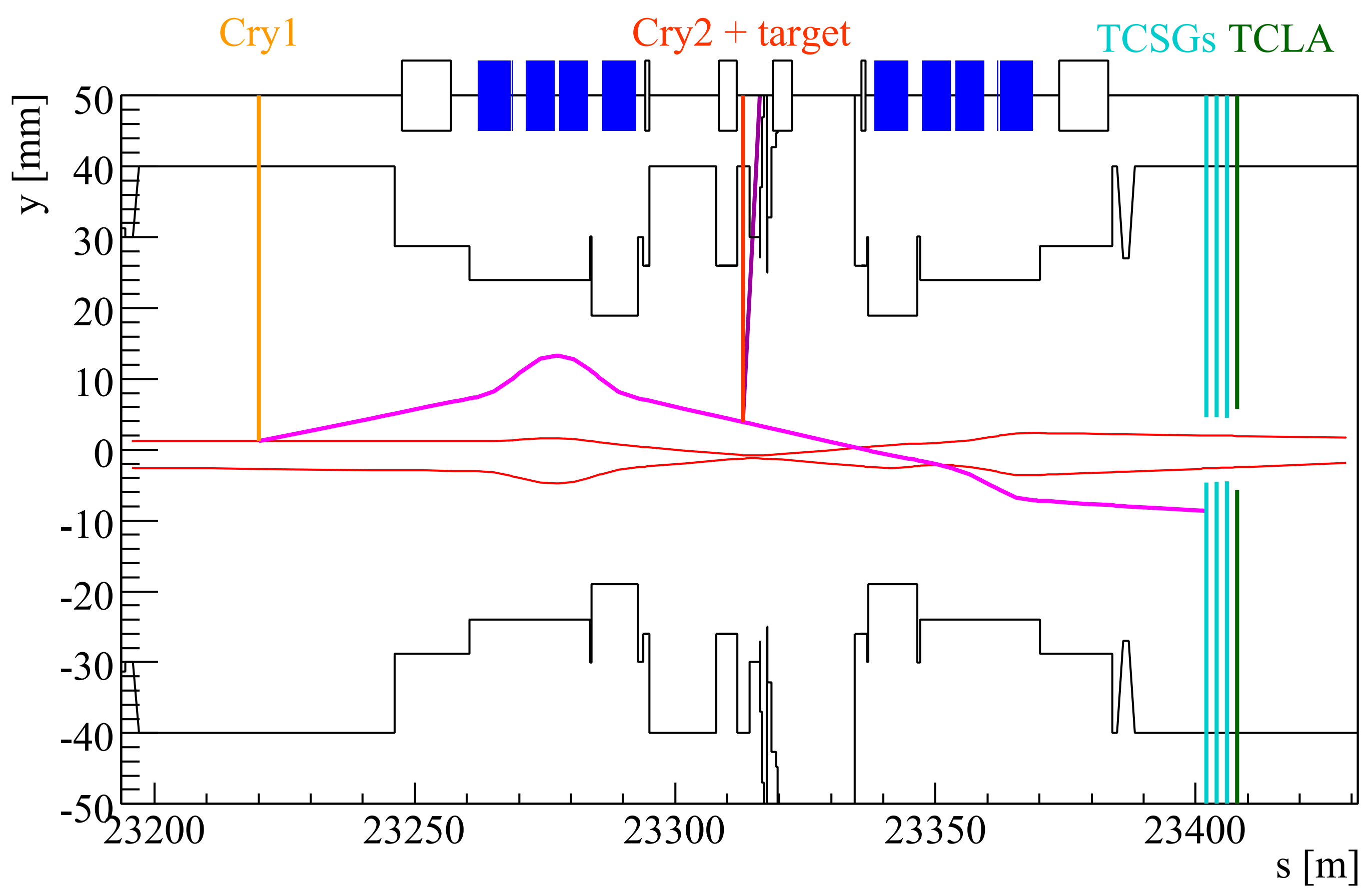
- **Observable: is the loss pattern affected by** the insertion of the Cry_1+target+Cry_2 assembly?
  - ✓ **NO**: measurements during standard physics operations could be allowed
    Parasitic operations
  - ✓ **YES**: limit on maximum stored intensity
    Dedicated operations
- LHC running configuration in 2018 used
  → Dedicated optics would imply dedicated operations

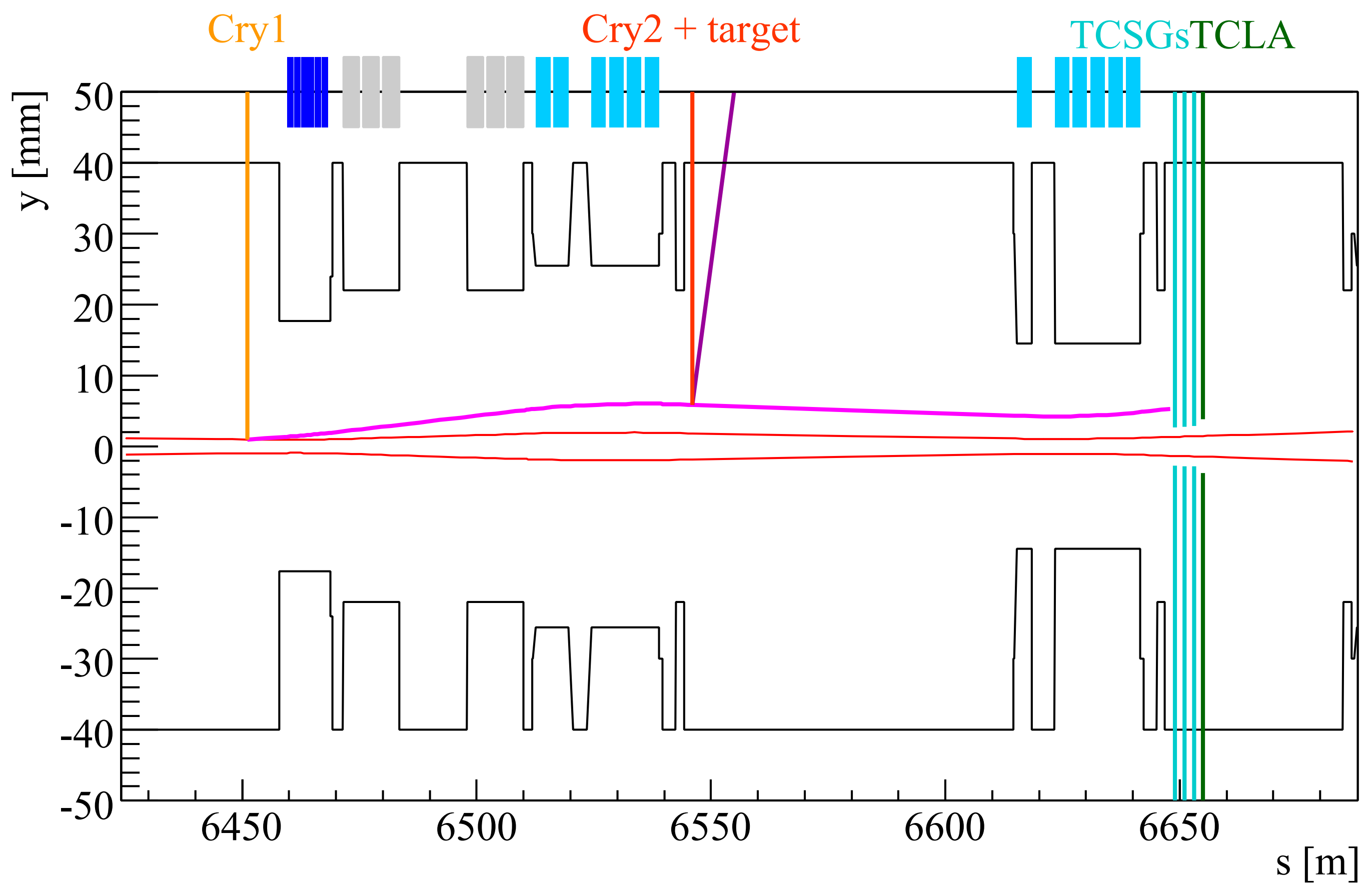


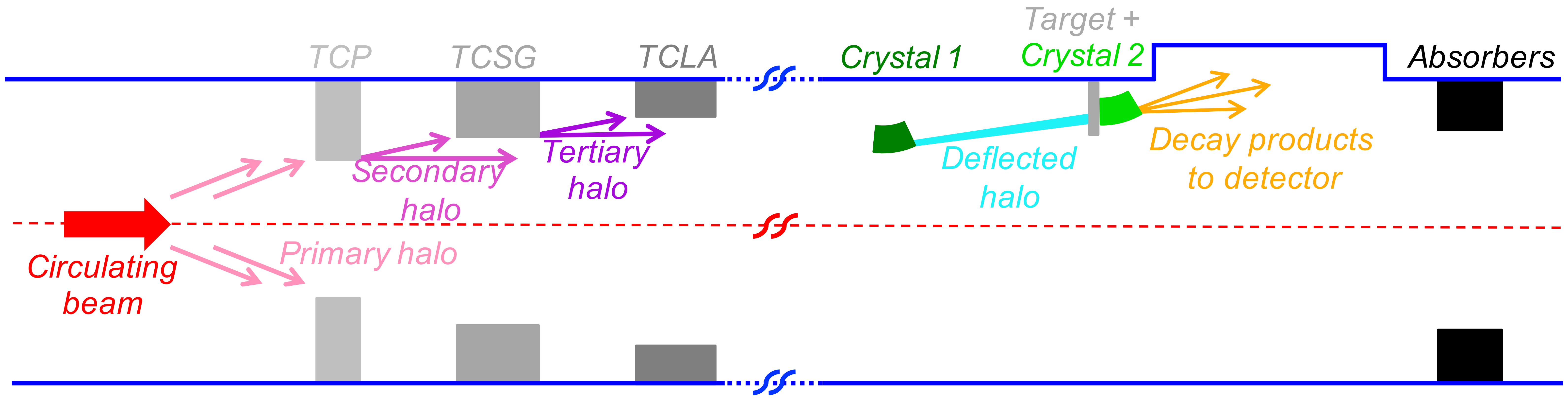


Fixed target at the LHC: Layouts for FT experiments and EMDM measurements

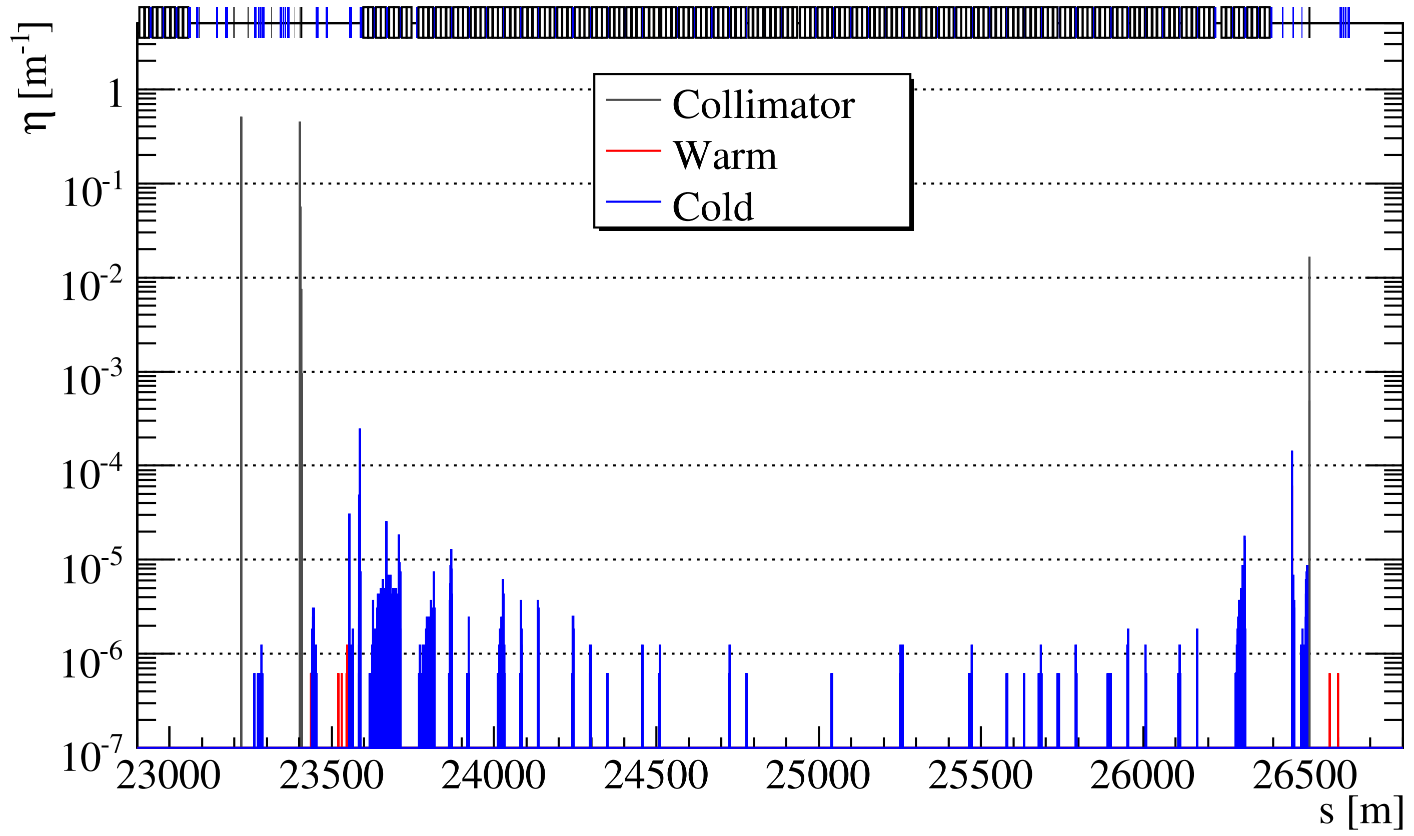
D. Mirarchi et al., Eur. Phys. J. C 80, 929 (2020)







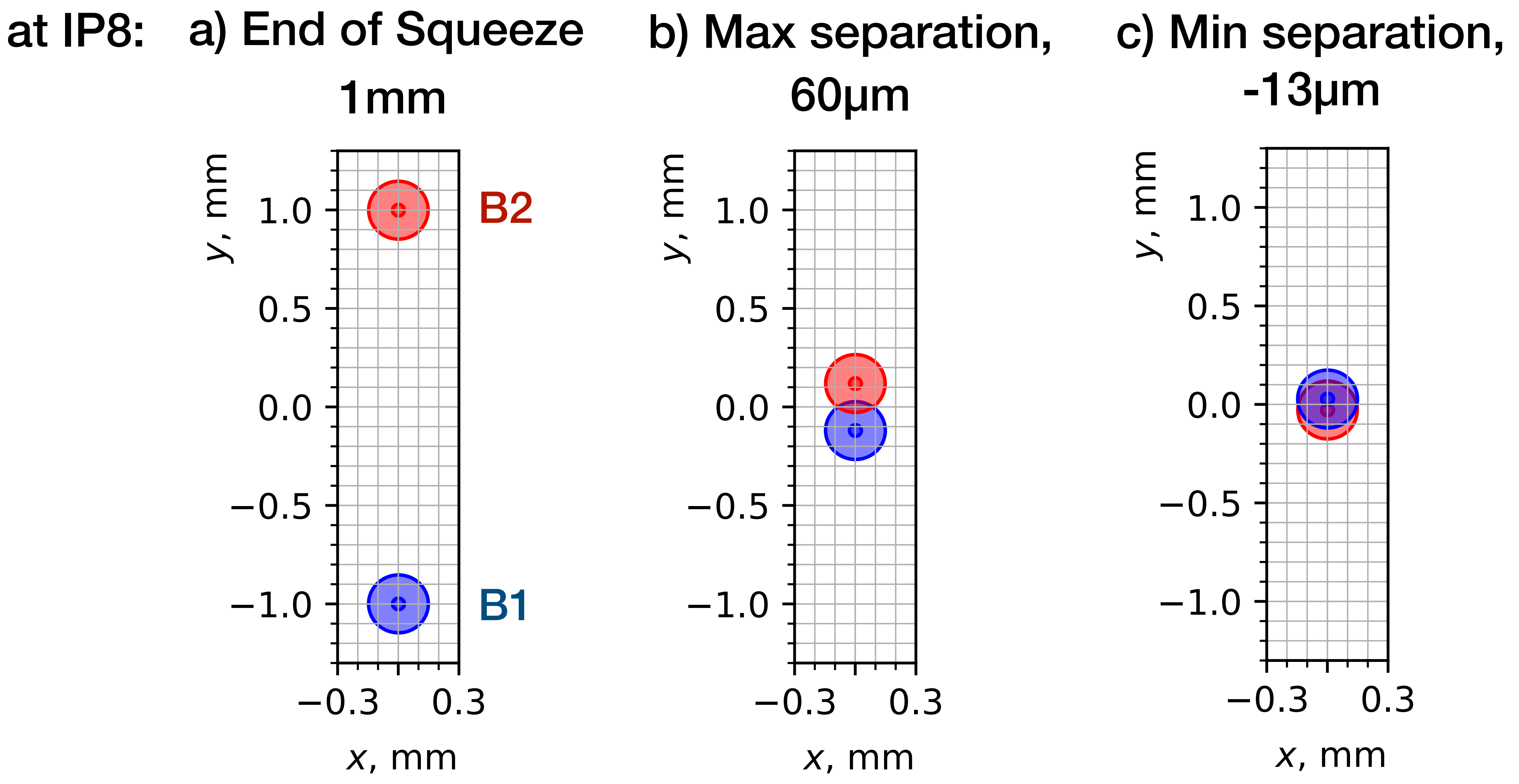
- impact on the machine (SixTrack simulation)
- optimisation of Crystal 1 and Absorbers positions
- running experiment in a parasitic mode with 0.5 σ retraction of Crystal 1 w.r.t. TCP
- layout in front of LHCb (IR8) 4.3×10^{10} POT/fill
- alternative layout at IR3 3.0×10^{10} POT/fill
- advantage in Λc production in IR3

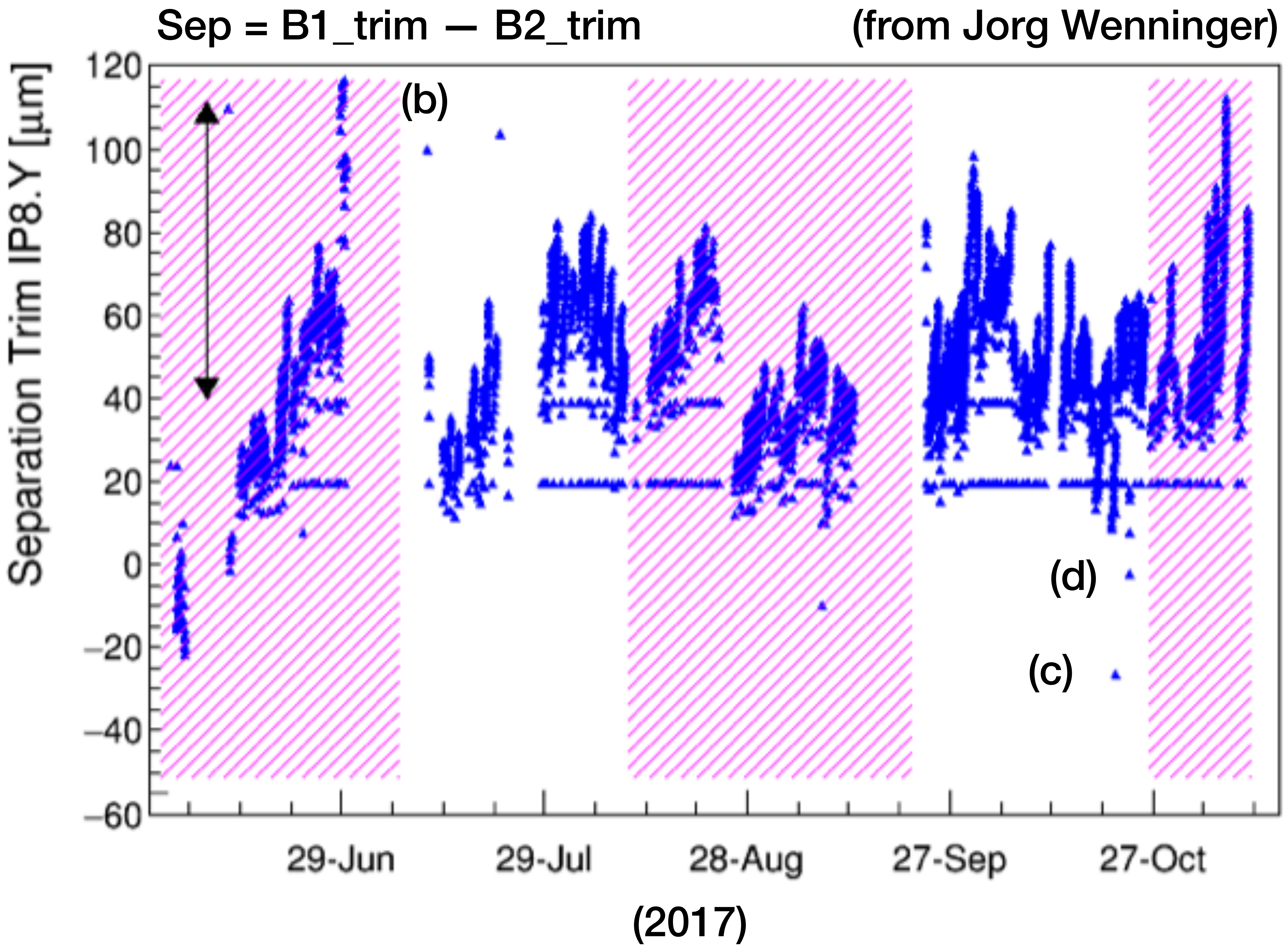


Considerations for layout at LHCb:

Dynamic changes during levelling

Dynamic changes during levelling

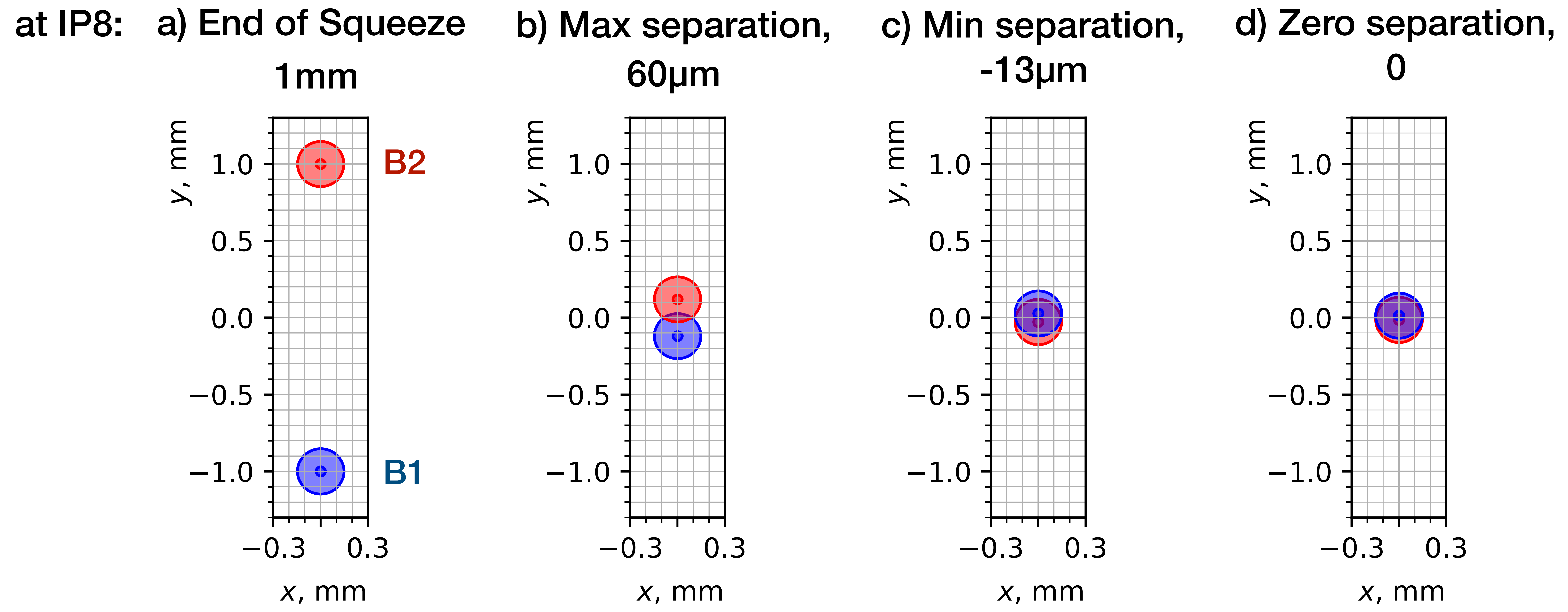


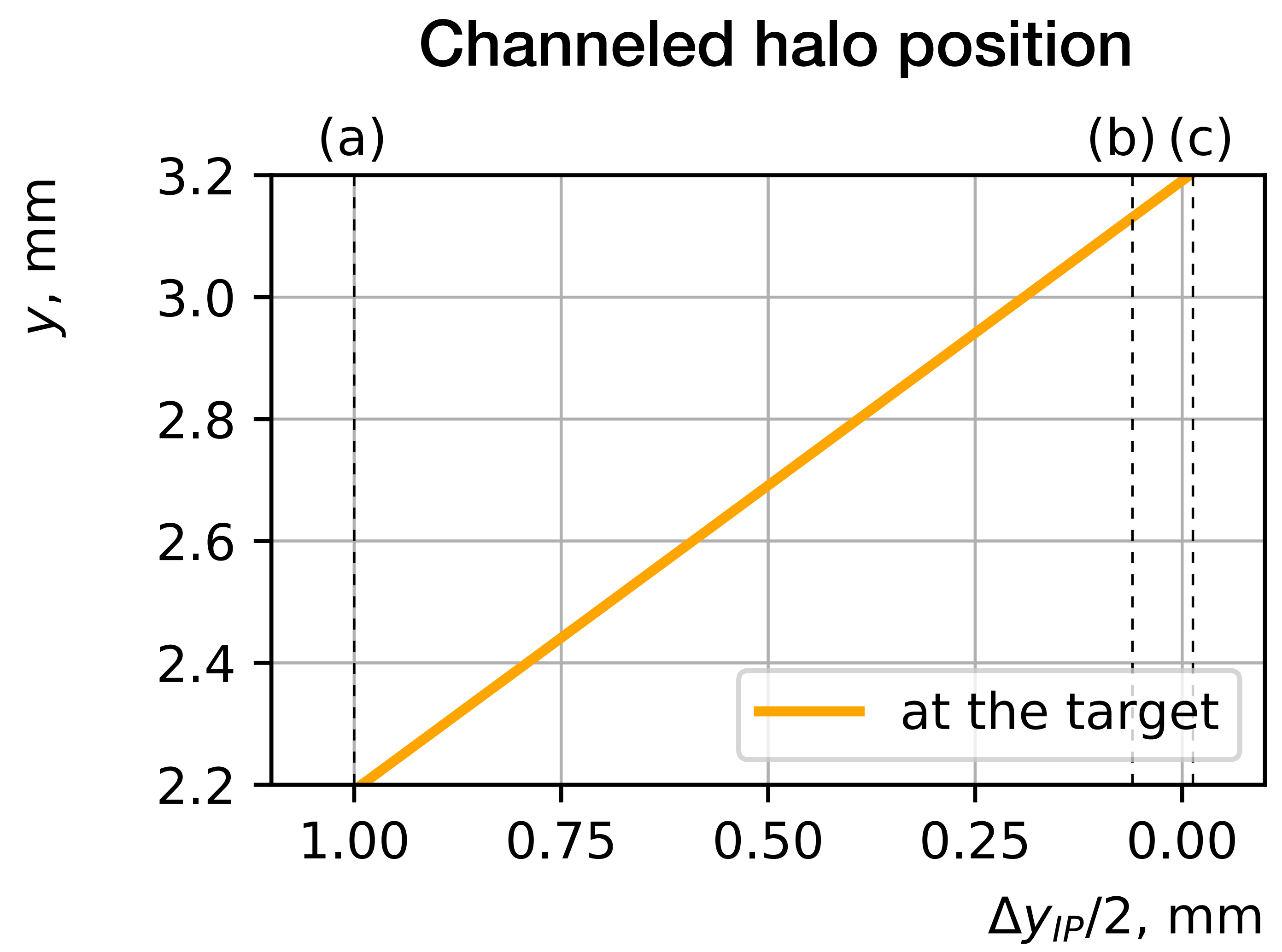


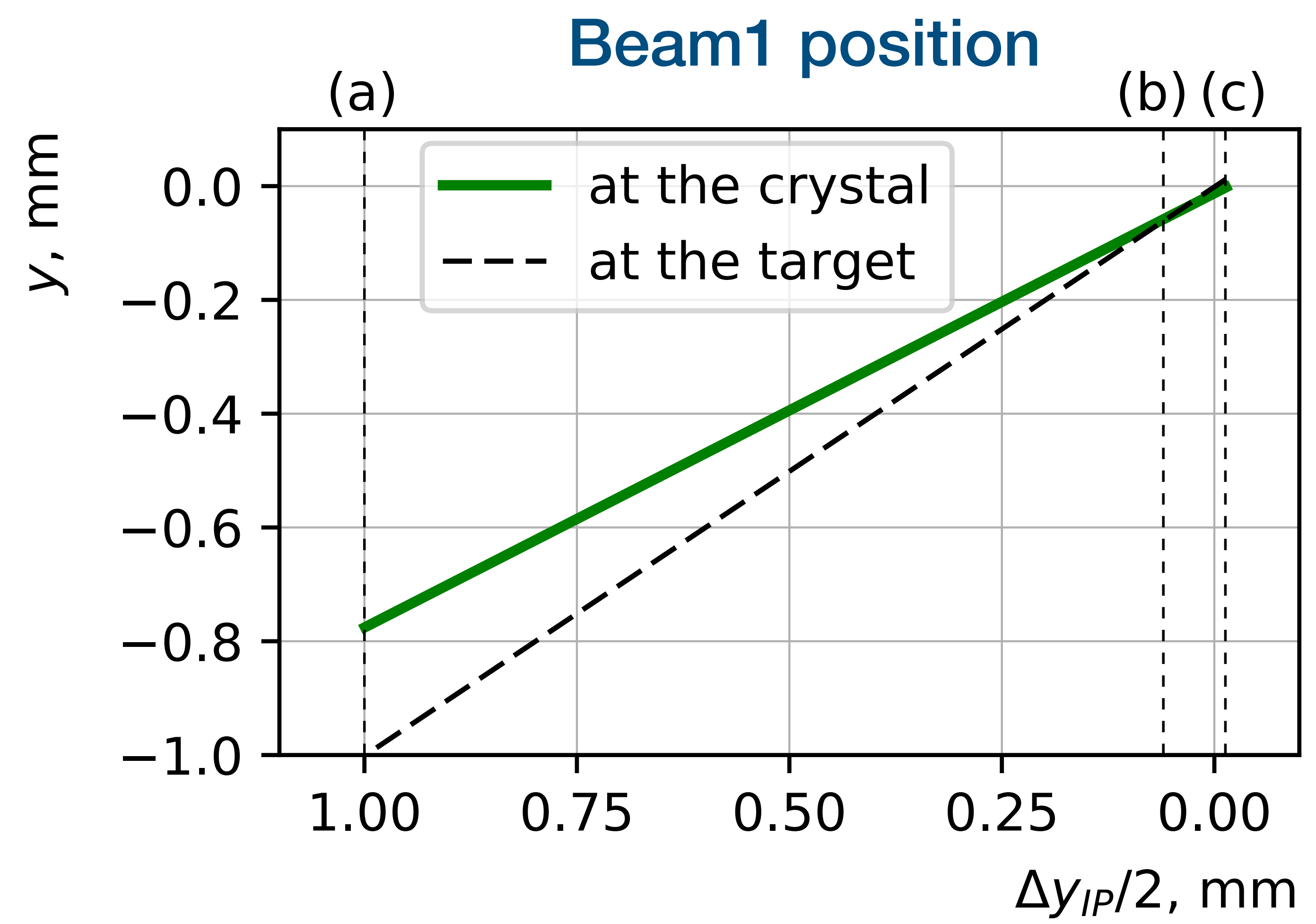
Beam separation, Δy_{IP}		
at the IP8		
	mm	σ (0.03 mm)
a) End of Squeeze	1.00	34
b) Max separation	0.06	2
d) Zero separation	0.0	0
displacement during levelling	0.06	2

* Optics of 2018 machine configuration at "Stable Beam"

Dynamic changes during levelling: beam and channeled halo displacements







Beam separation, Δy_{IP}			Beam 1 position, y			Deflected beam, y	
at the IP8			at the Crystal 1		at the Target		
	mm	σ (0.03 mm)	mm	σ (0.3 mm)	*mm*	mm	σ (0.04 mm)
a) End of Squeeze	1.00	34	-0.78	-2.62	*-1.00*	2.20	58
b) Max separation	0.06	2	-0.05	-0.16	*-0.06*	3.12	83
d) Zero separation	0.0	0	0.00	-0.01	*0*	3.20	85
displacement during levelling	**0.06**	**2**	**0.05**	**0.15**		**0.08**	**2**

- Optics of 2018 machine configuration at "Stable Beam"

Dynamic changes during levelling: beam and channeled halo displacements

Displacement of Beam 1 during the fill due to levelling

- at Crystal 1 is ~0.15 σ → should be taken into account
  as the secondary halo intensity grows rapidly
  e.g. for Crystal 1 retraction 0.65 → 0.50 σ (w.r.t. TCP)

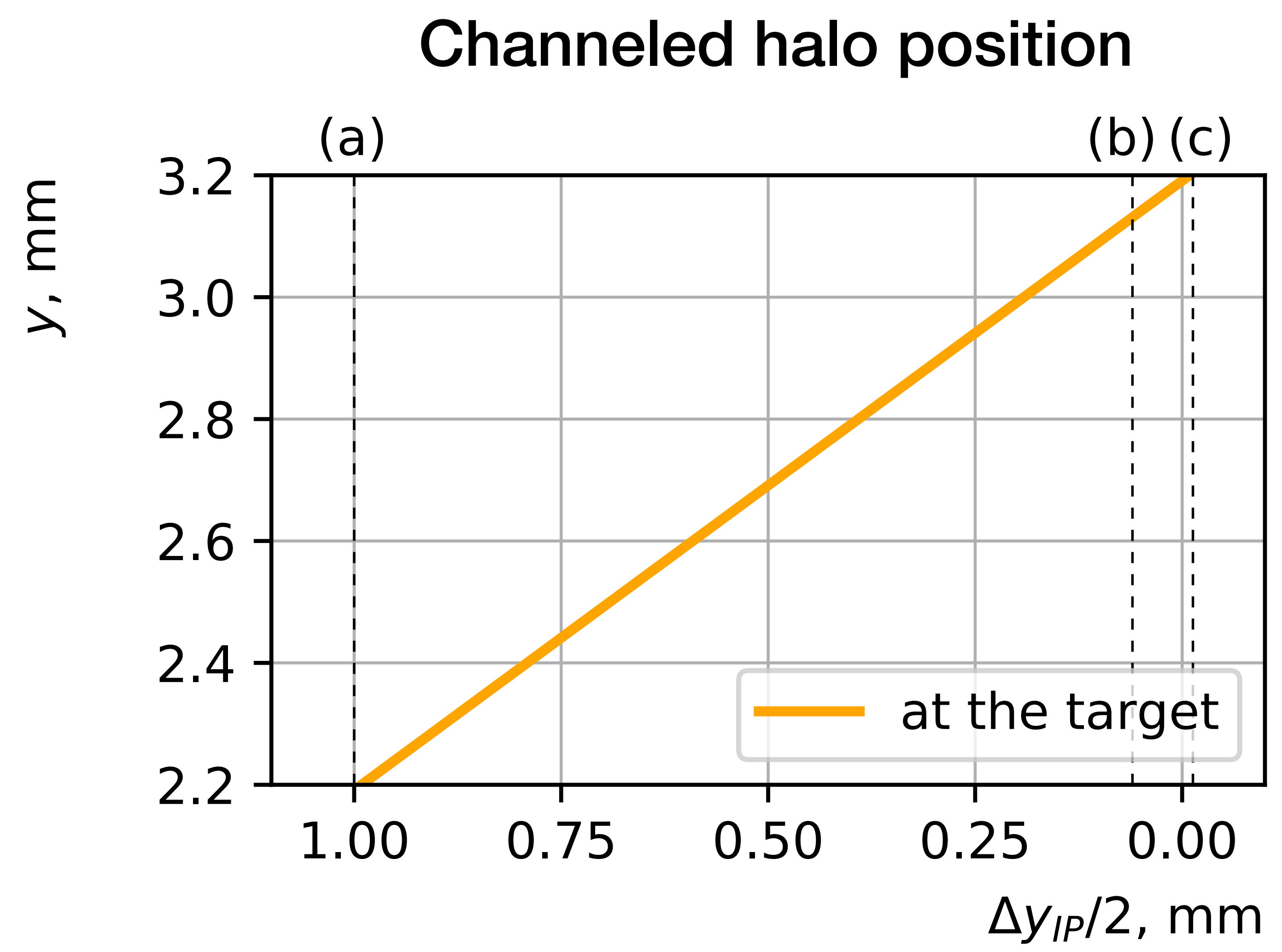
Displacement of deflected beam during the fill due to levelling

- at Target is ~80 μm → can be neglected

Optics for Run III are in preparation. Possible changes:

- spectrometer polarity
- the vertical crossing

→ Would require additional check



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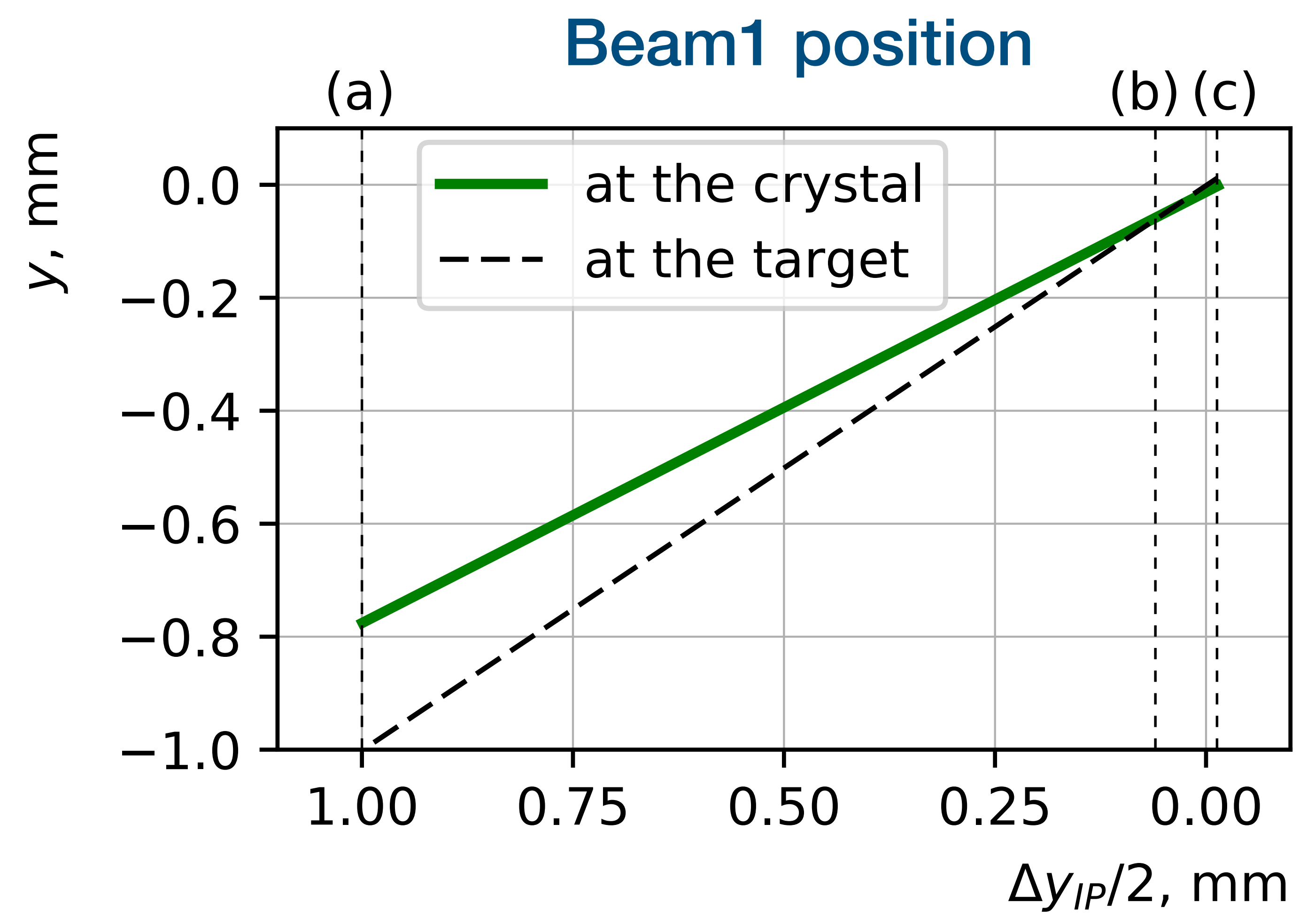


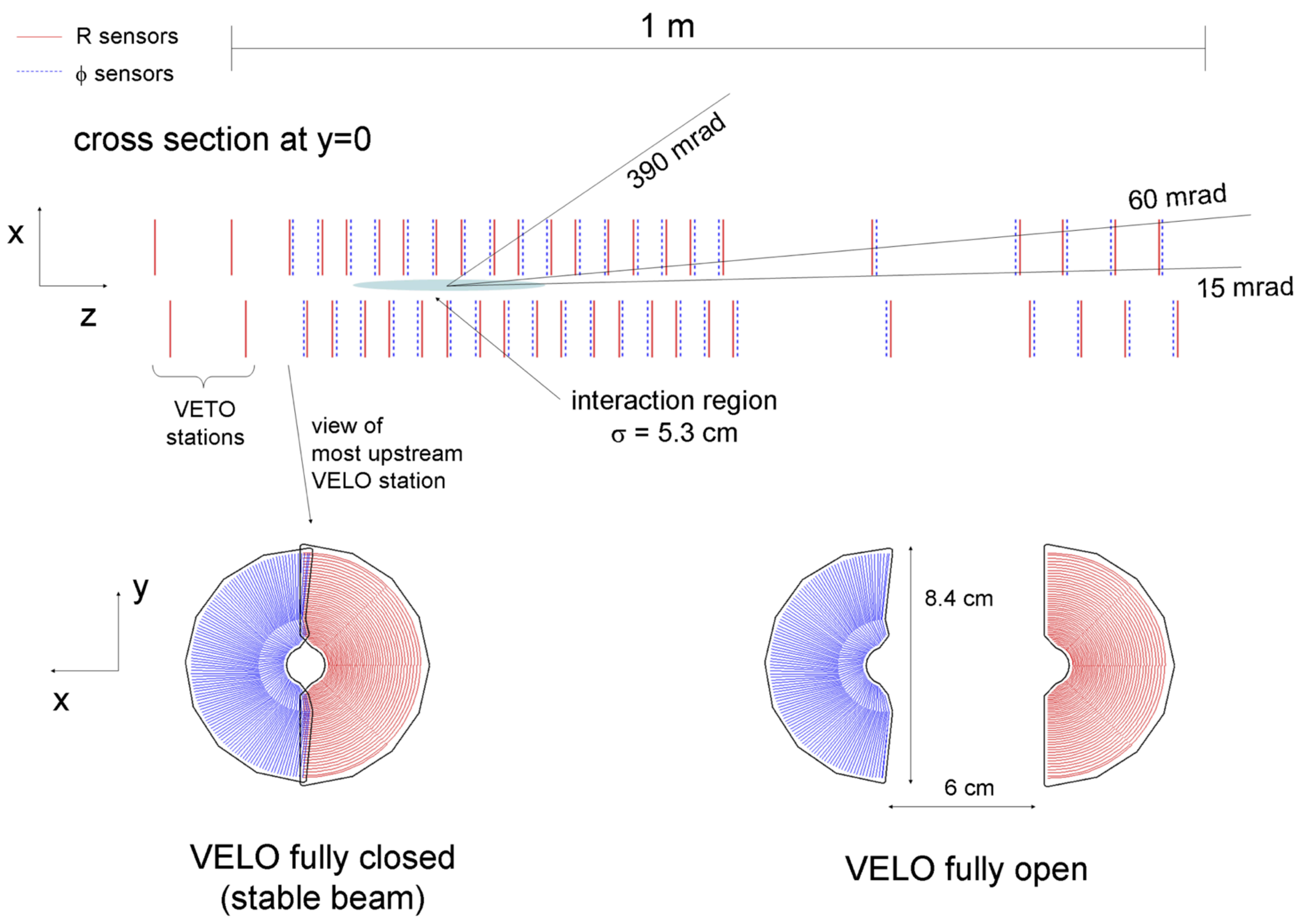
- Optics of 2018 machine configuration at "Stable Beam"

Considerations for layout at LHCb:

Channeled halo and new VELO aperture

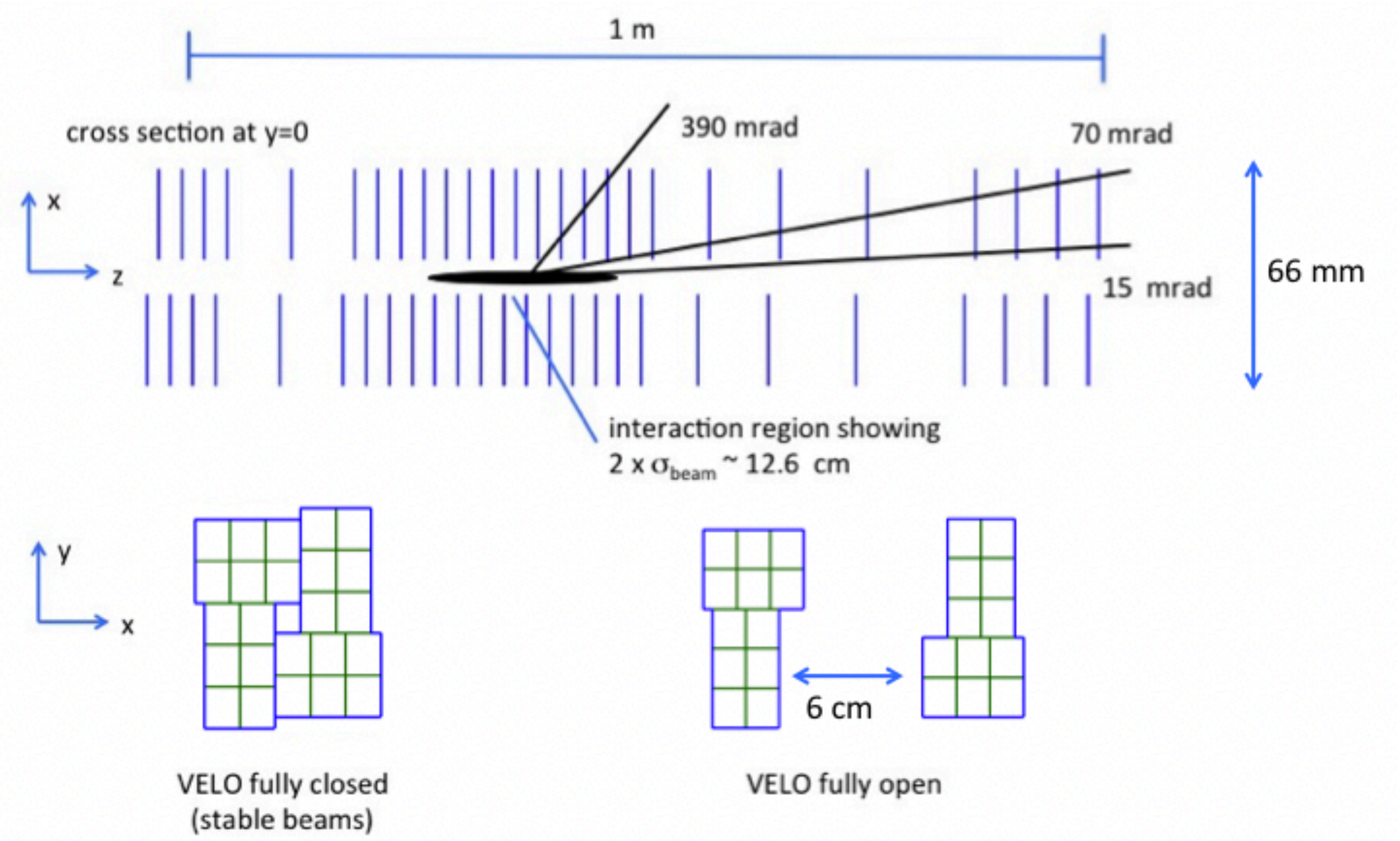
Upgraded VELO aperture: ~5 mm → 3.5 mm

LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.



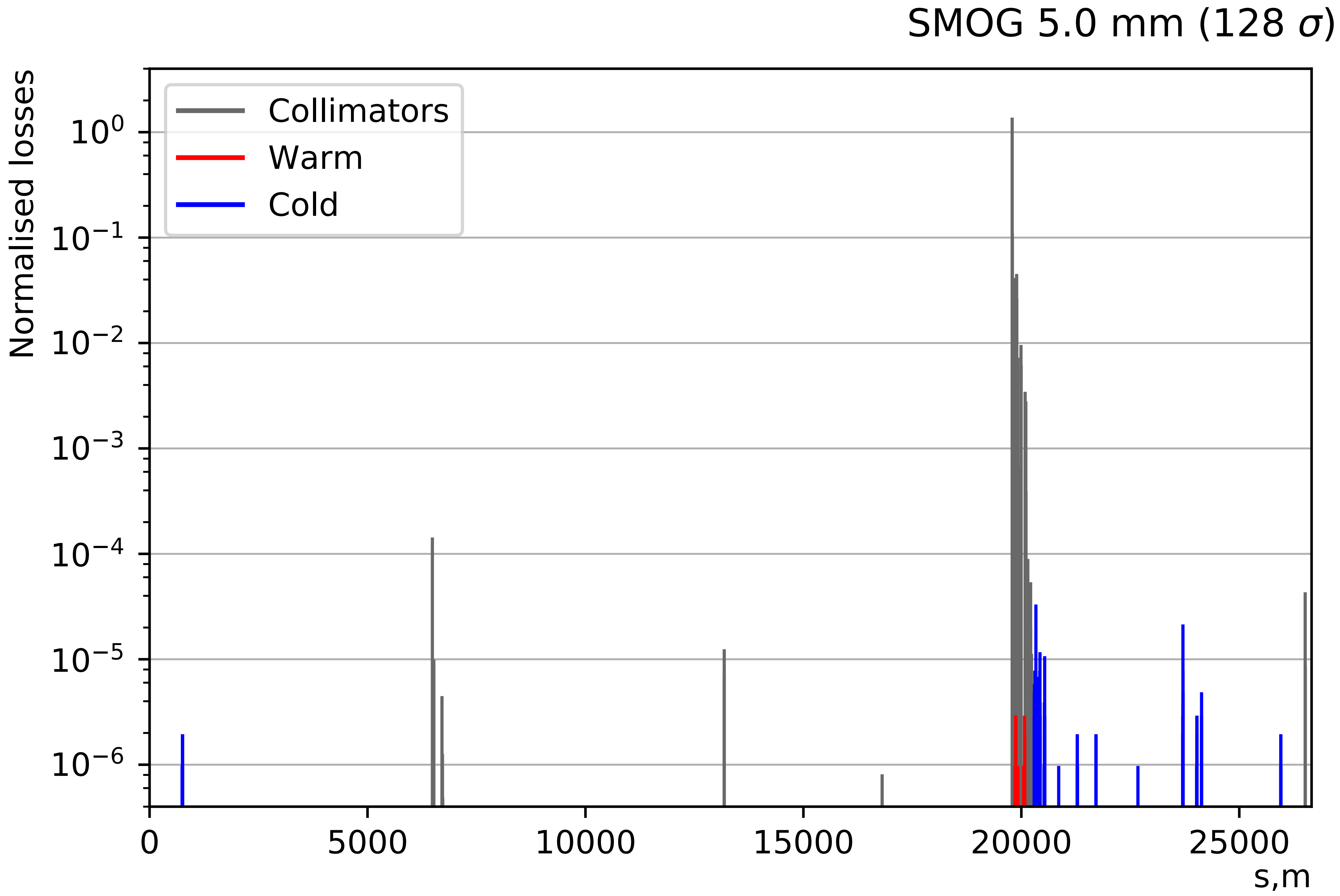
- the old VELO foil inner radius ranges between 4.9 and 5.6 mm, as determined from particle interaction tomography

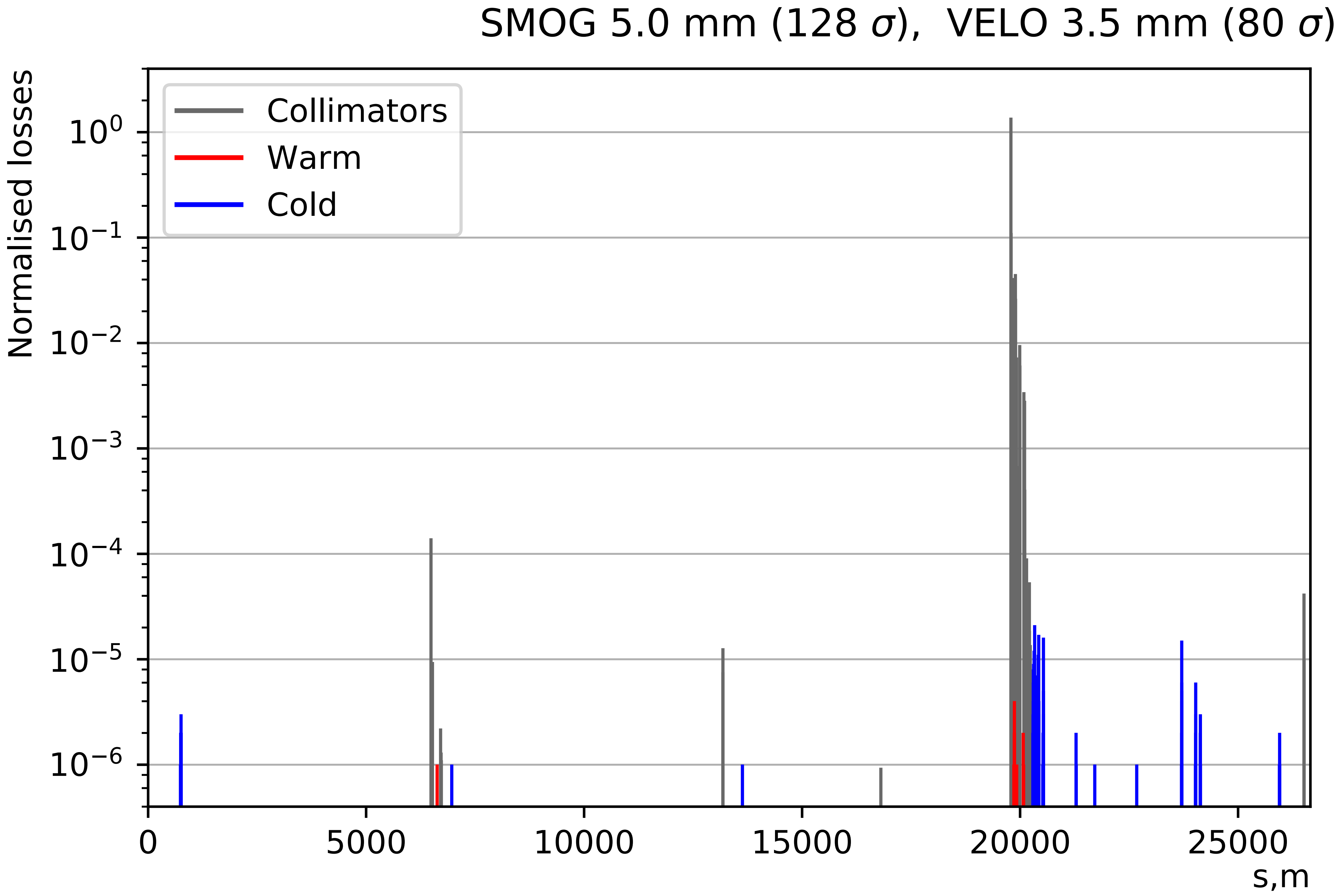
CERN/LHCC 2013-021, LHCb TDR 13, November 29 2013



- an inner foil radius of 3.5 mm was proposed and agreed upon
- a closest distance of approach to the LHC beams of just 5.1 mm for the first sensitive pixel

Upgraded VELO aperture: Loss maps   (no crystal)



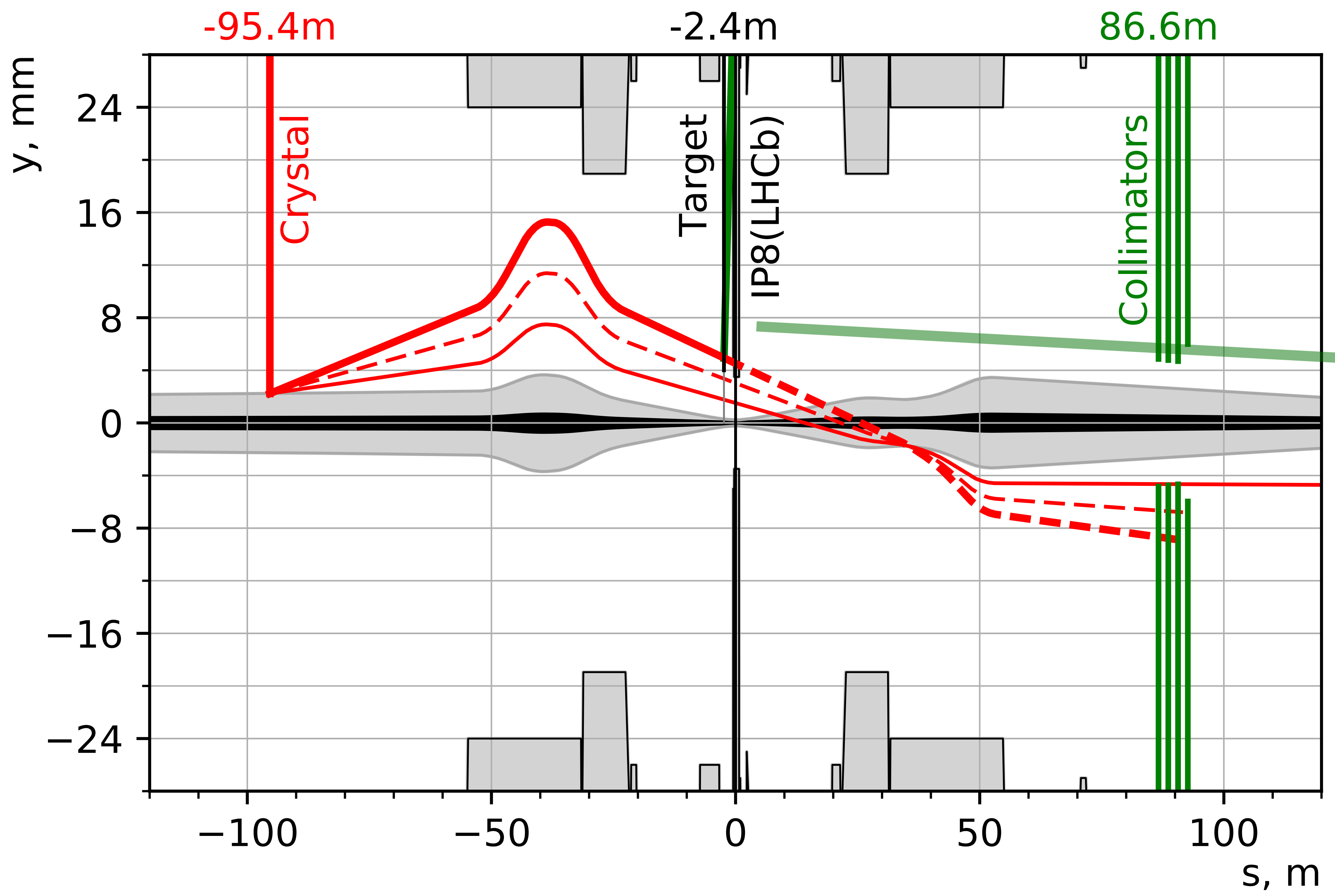


- SixTrack simulation with a new VELO aperture: 3.5 mm (80 σ, emit = 3.5 μm)
- No additional losses during the normal operation
- For a double crystal setup the additional check is needed

- Optics of 2018 machine configuration at “End of Squeeze”

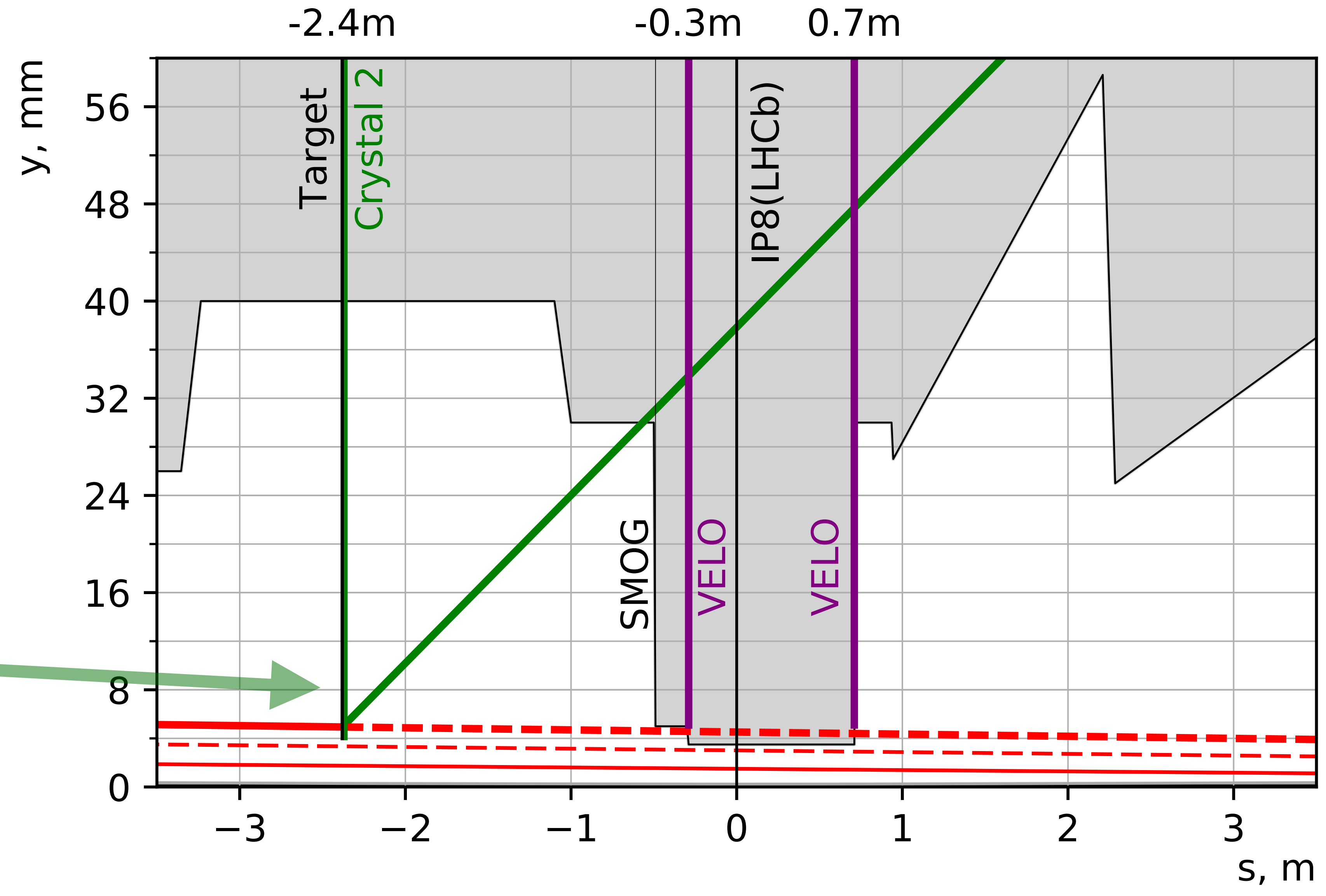
Channeled halo and new VELO aperture

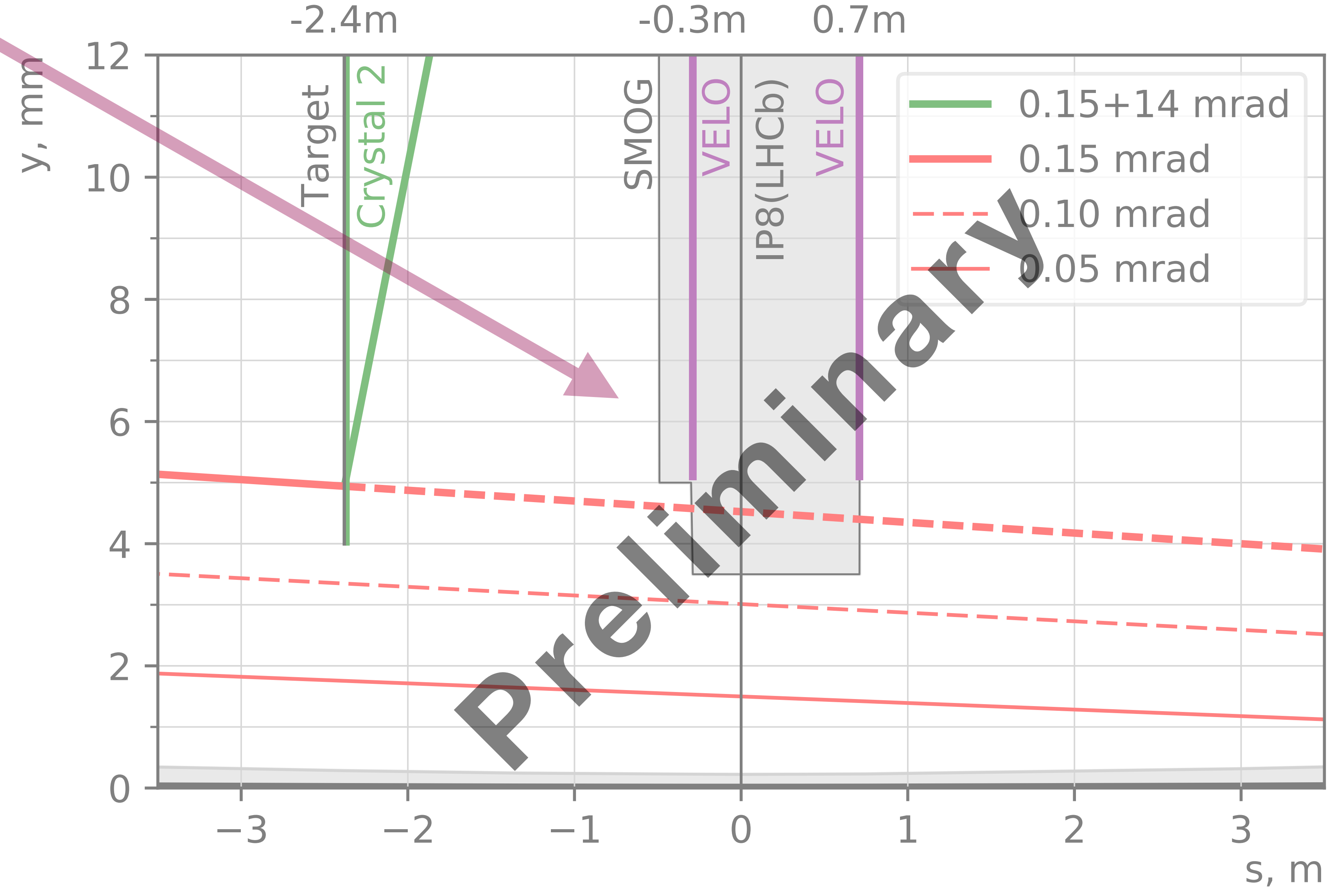
Double crystal layout considered in D. Mirarchi et al., Eur. Phys. J. C 80, 929 (2020)



zoom on IP8

with updated VELO aperture

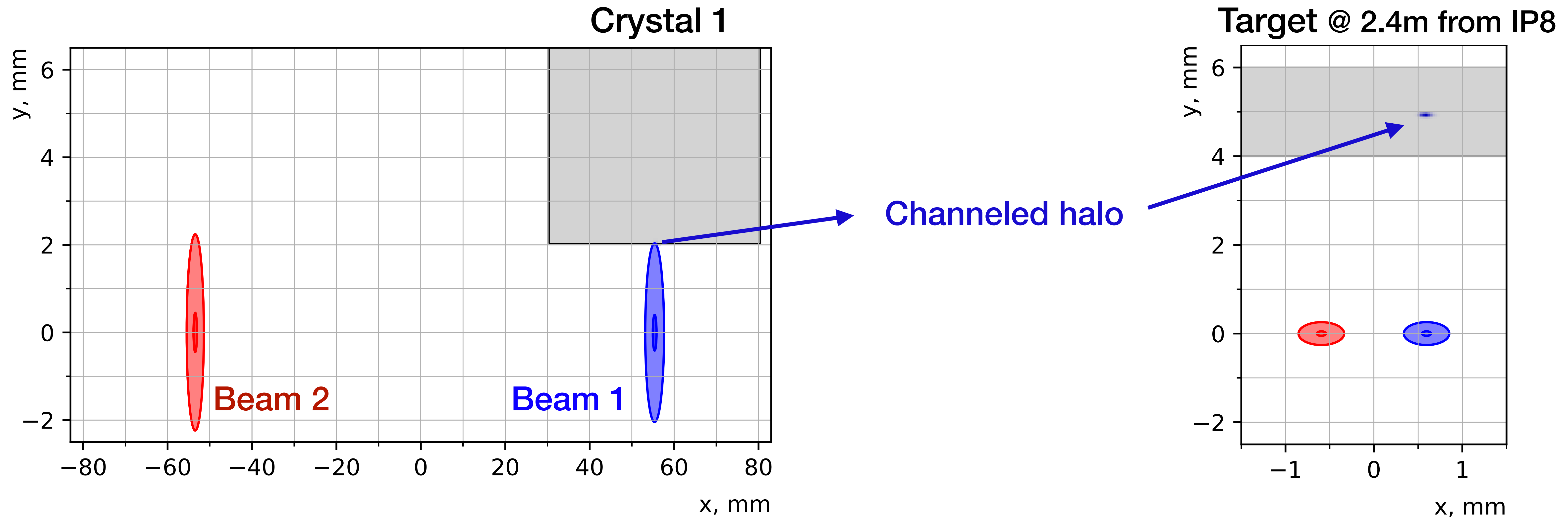


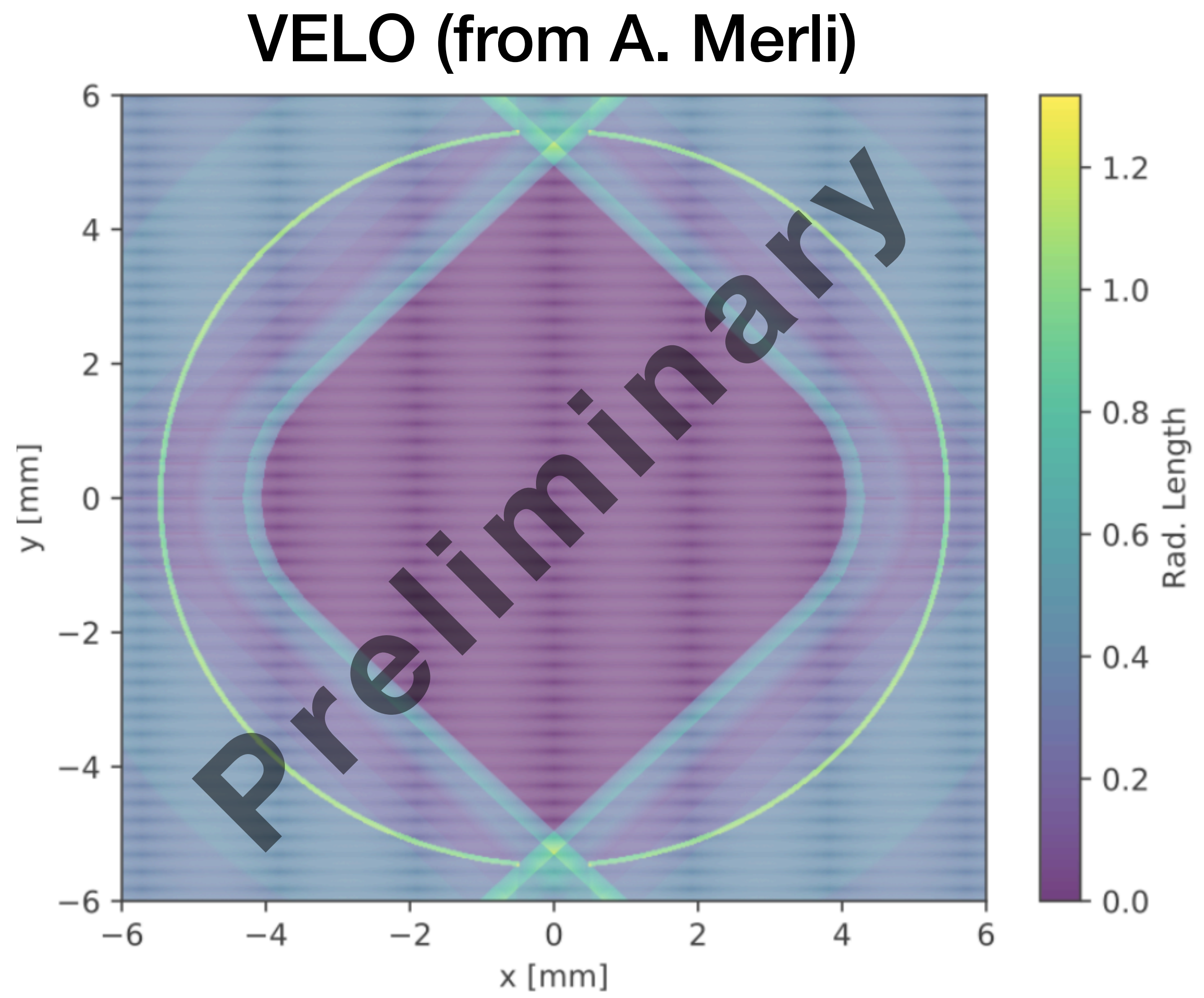


Preliminary result:

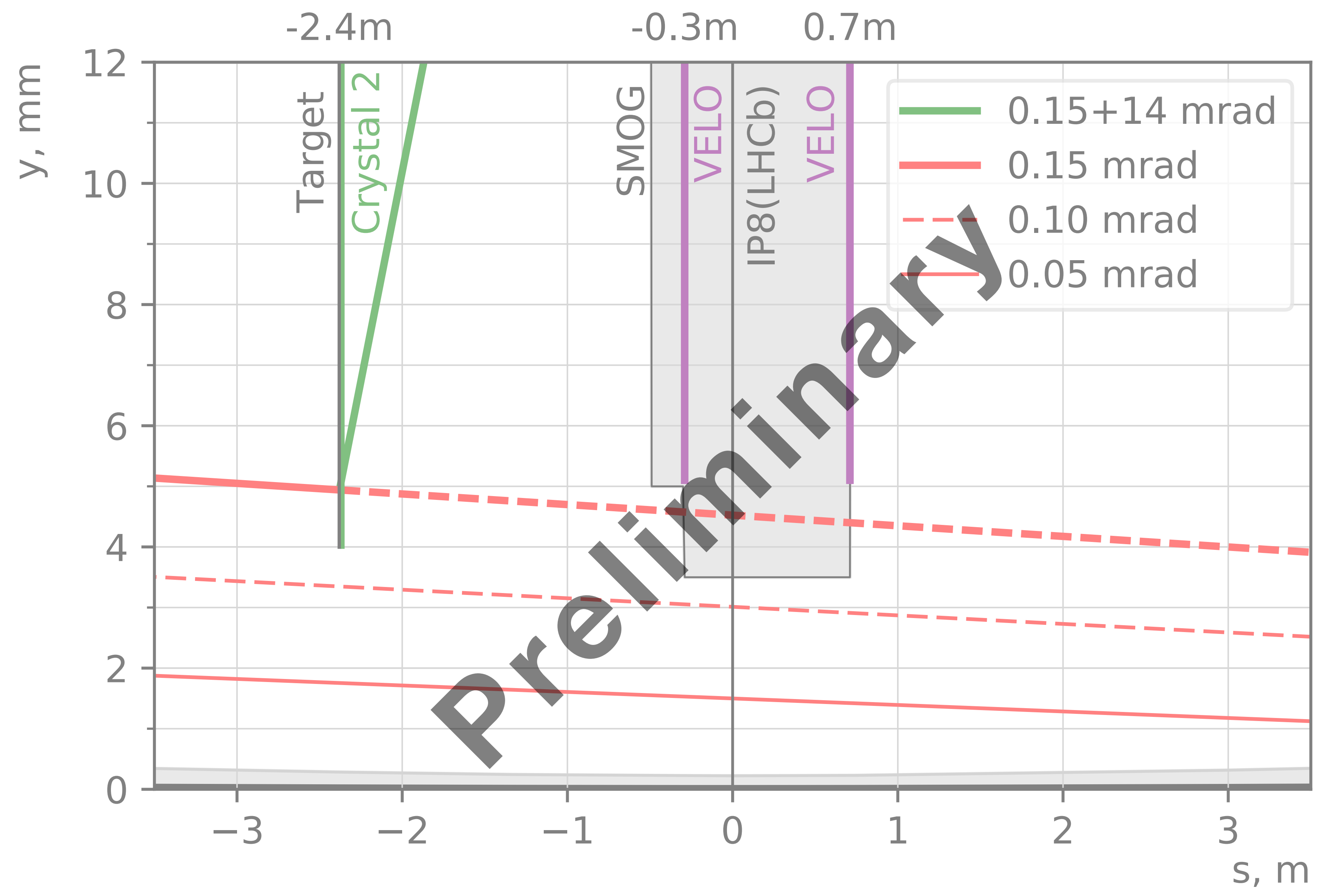
The channeled halo does not hit the SMOG and new VELO aperture (work is ongoing)

Channeled halo and new VELO aperture: beams positions



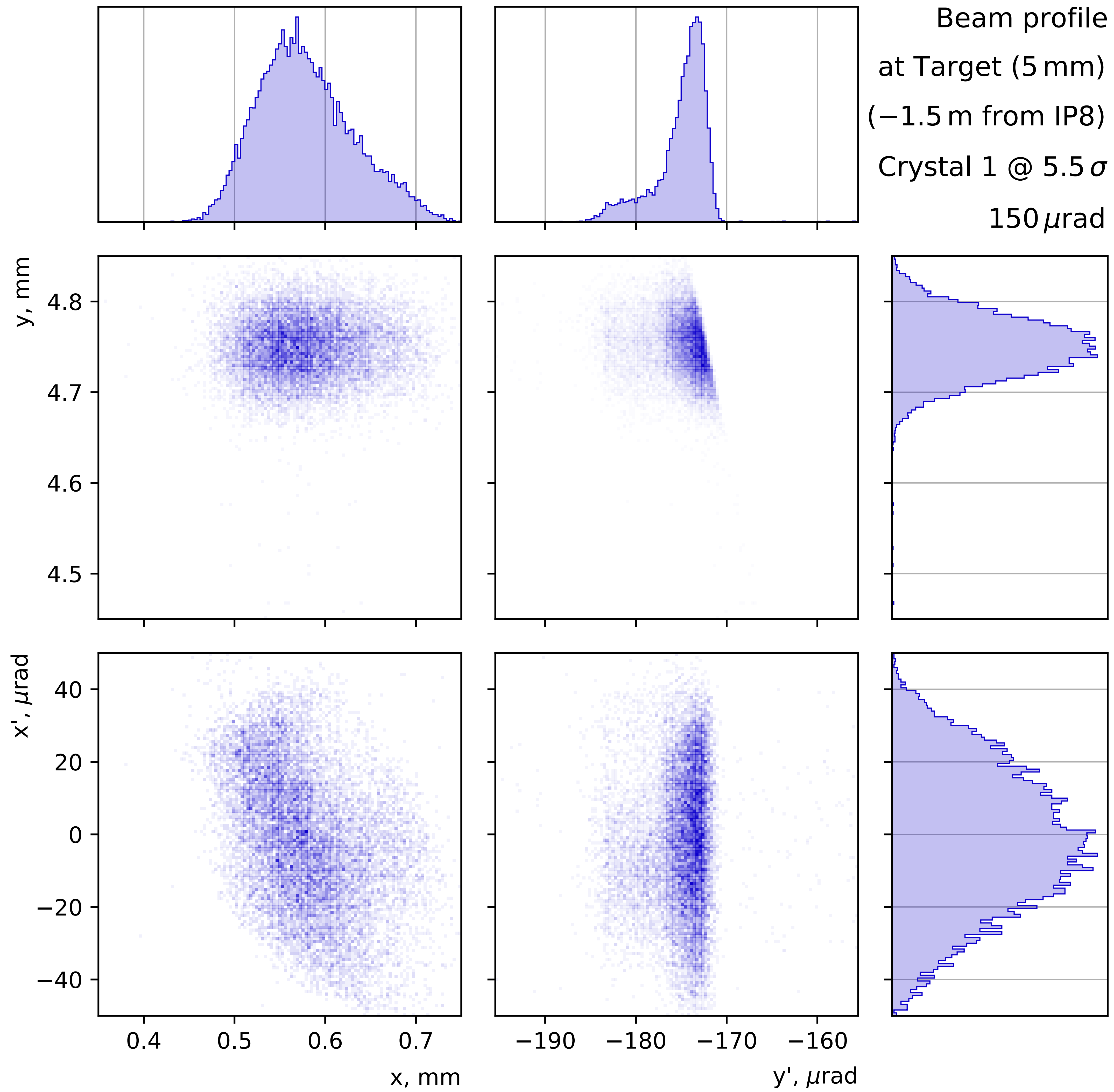


- Optics of 2018 machine configuration at “Stable Beam” used for all simulations
- Evaluation to be performed also with RunIII configurations when frozen
- Space is tight and conflicts between the two beams have to be studied for a final design of the crystal support/holder (common beam pipe)
- The channeled halo does not hit the new VELO aperture (preliminary result)

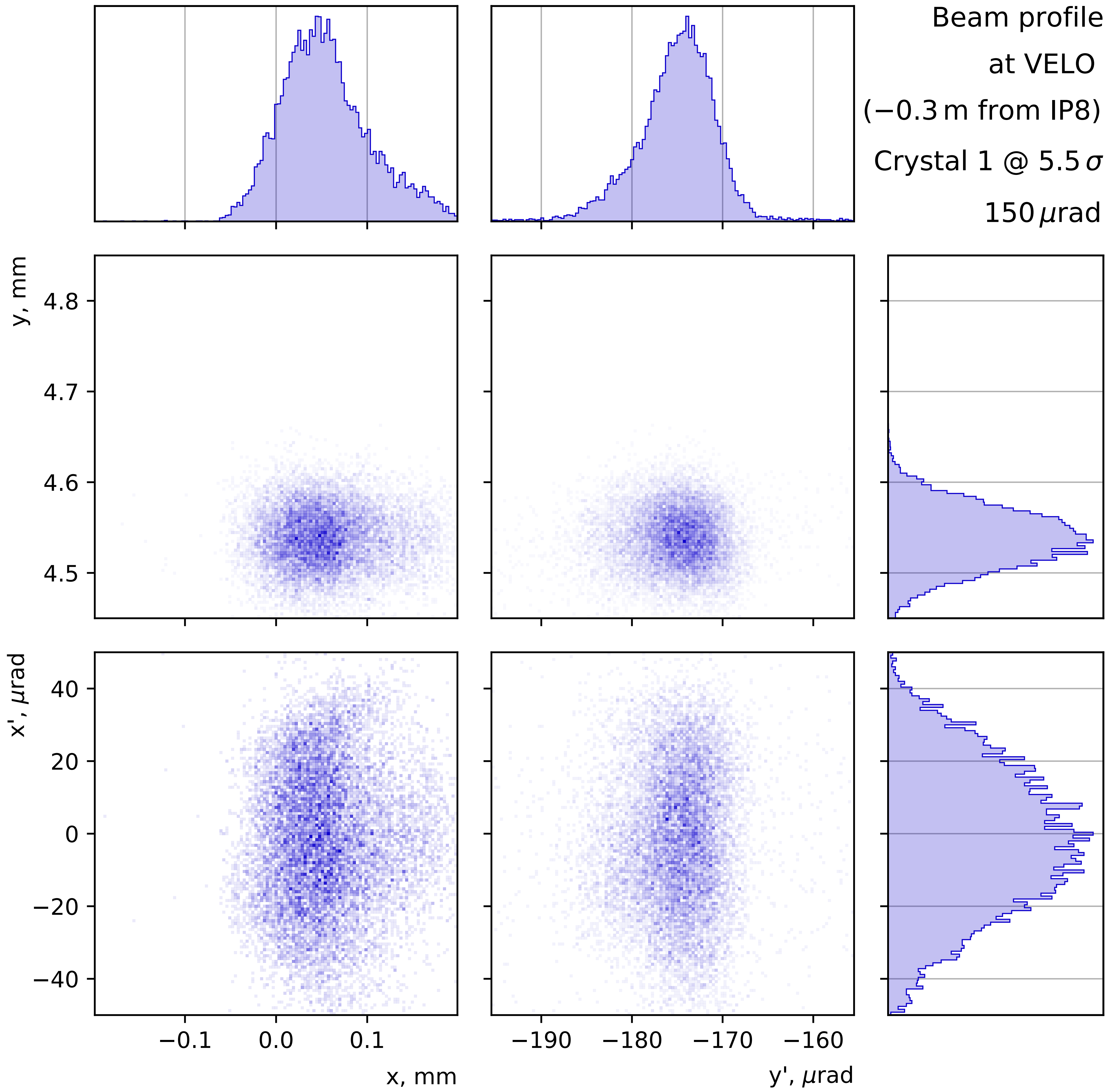


Channeled halo and new VELO aperture: deflected beam profile

Max. flux of protons on Target: ~1.6x10⁶ p/s (~1.6x10⁹ p/s for 10s)

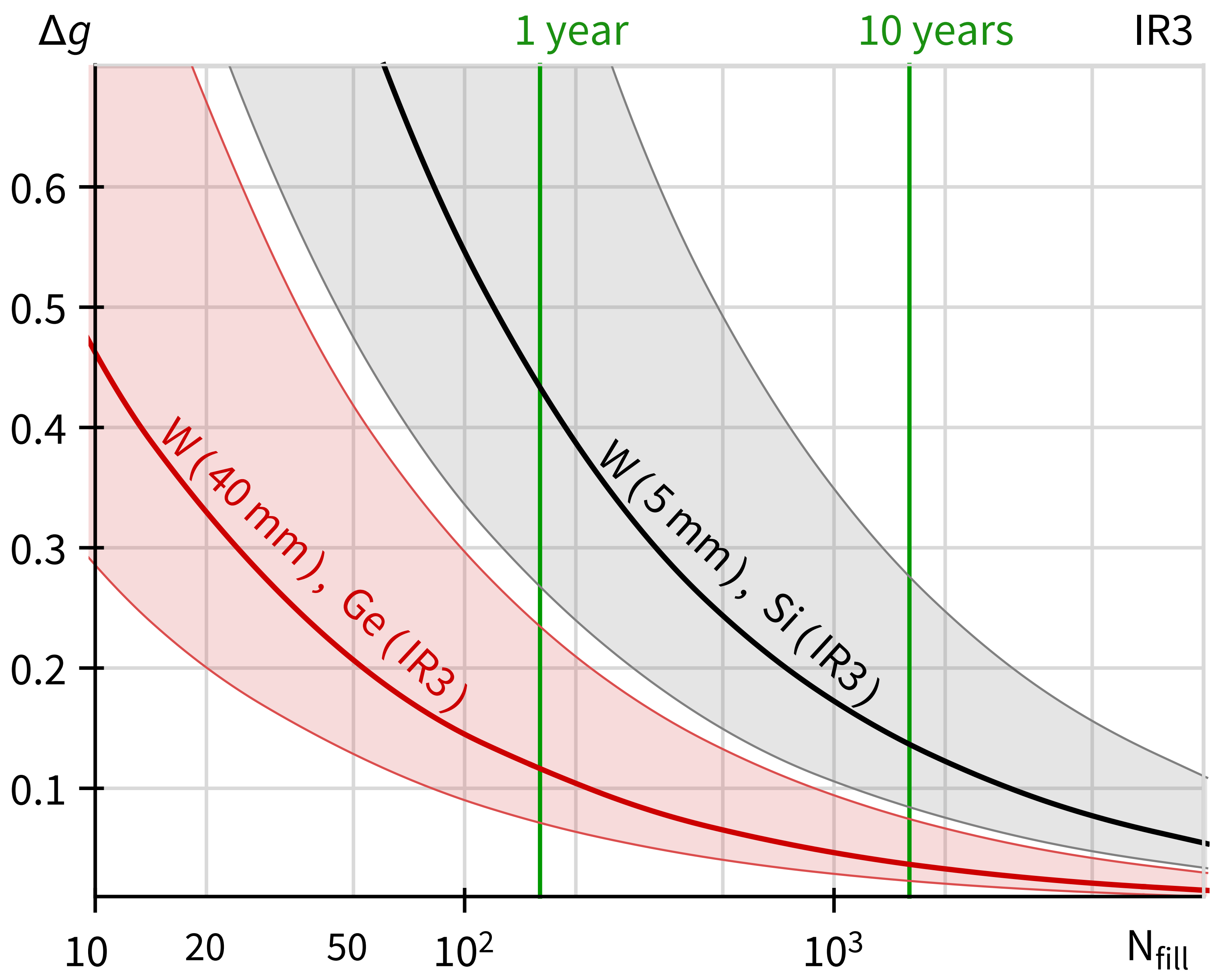


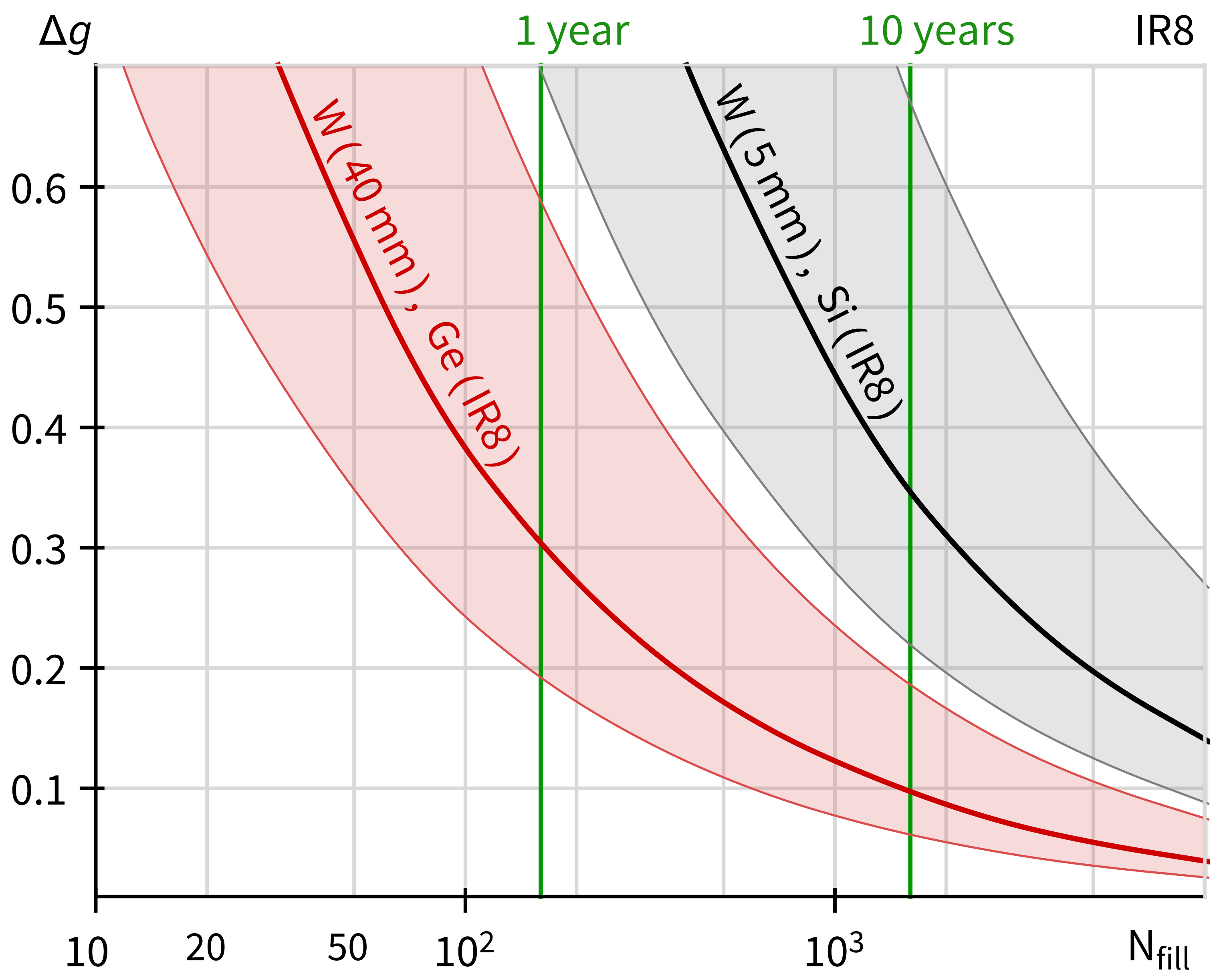
Max. flux of protons at VELO: ~1.5x10⁶ p/s (~1.5x10⁹ p/s for 10s)



Possible improvements of double crystal setups efficiency

Possible improvements of double crystal setups efficiency





A. Fomin et al. Eur. Phys. J. C (2020) 80:358

- optimal orientation of Crystal 2 for EDM: data taking time reduced by ~170
- thicker target 5 mm → 40 mm: ionisation energy losses and multiple scattering can be neglected, showers production - to be checked

- 10 year at LHCb, 5mm, Si → Δg ~ 0.35
- 1 year at IR3, 40mm, Ge → Δg ~ 0.12
- big uncertainty (×10) due to α parameter
- 10 years at IR8, 40mm, Ge, $\Delta d \sim 2.6\ 10^{-16}$ e cm

Possible improvements:

	1 → 2	t1/t2
Target	**5 mm → 40 mm**	**6**
Crystal	silicon → germanium	2.4
Detector	LHCb (IR8) → dedicated at IR3	7.5
Beam exitation	currently under study	…

Possible improvements of double crystal setups efficiency: update

Optimal Target Length

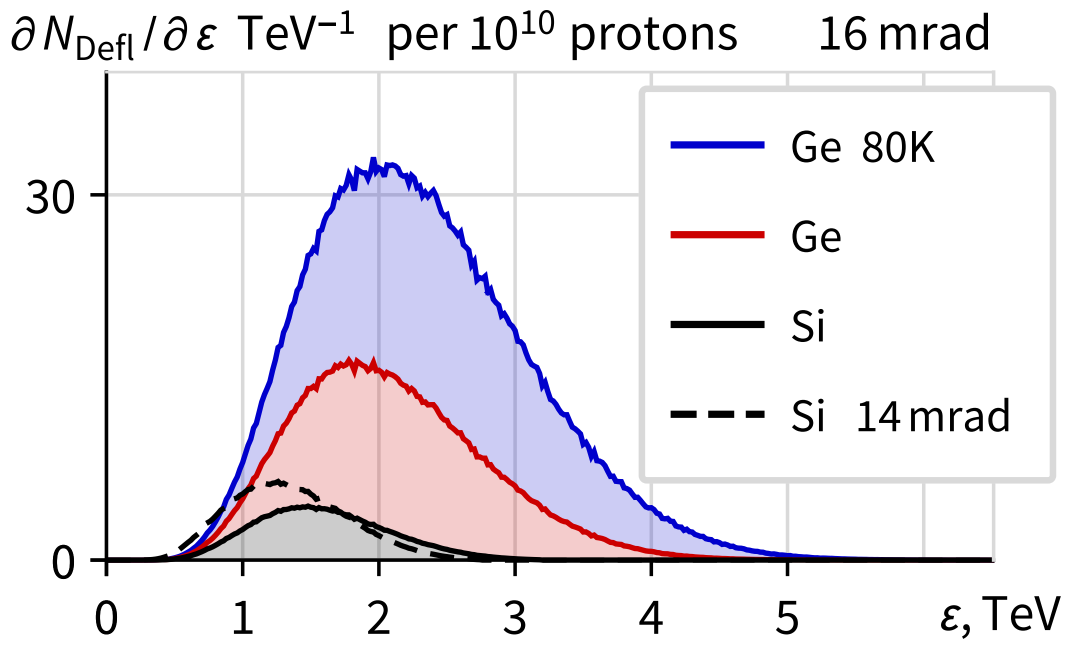
- Longer target (0.5 cm → 4 cm) ⇨
  reduction of measurement time by a factor 4.0 (IR3) and 3.3 (IR8)

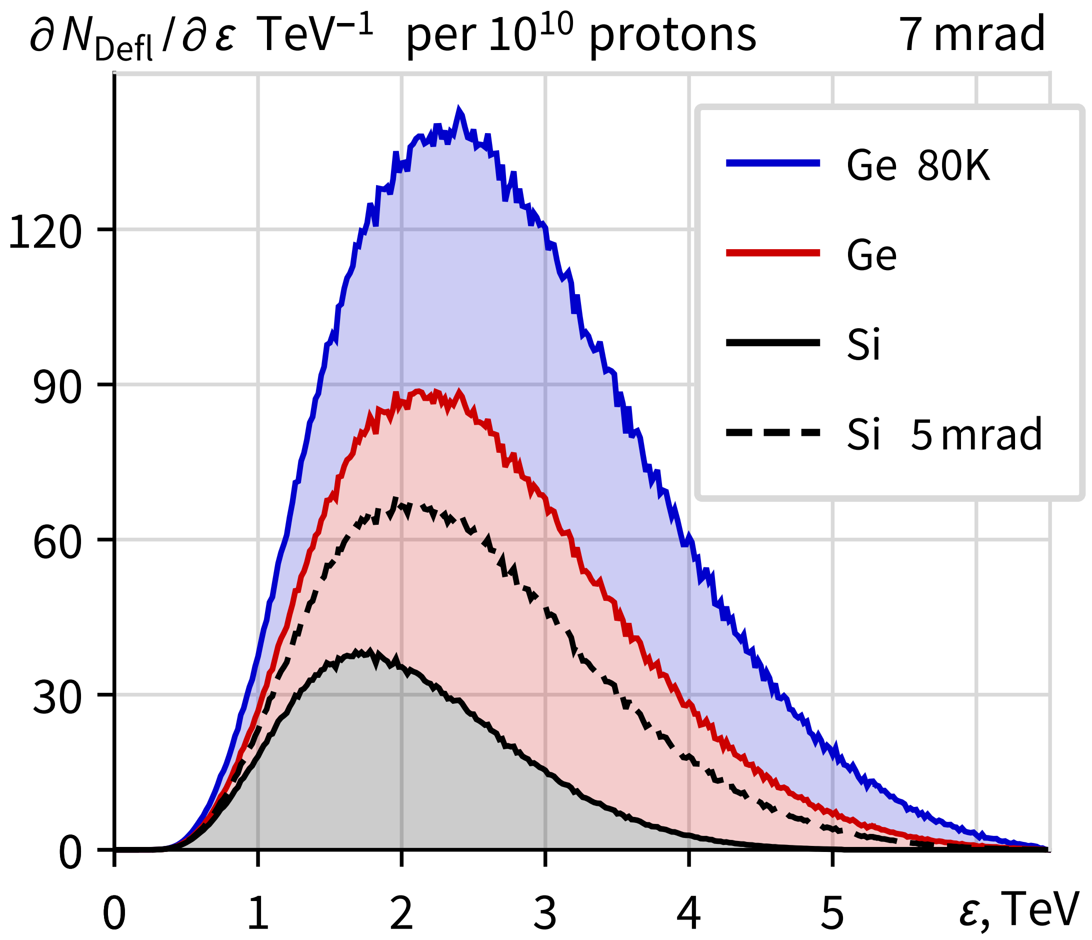
Optimal Crystal Parameters

- The small deflection angle is compensated by harder spectra and significantly greater statistics

	Si		Ge		Ge at 80K	
deflection angle, mrad	**16**	**7**	16	7	16	7
length, mm	100	70	100	70	100	70
reduction of data taking time	1	4.2	8.3	18	23	35

Spectra of deflected Λc





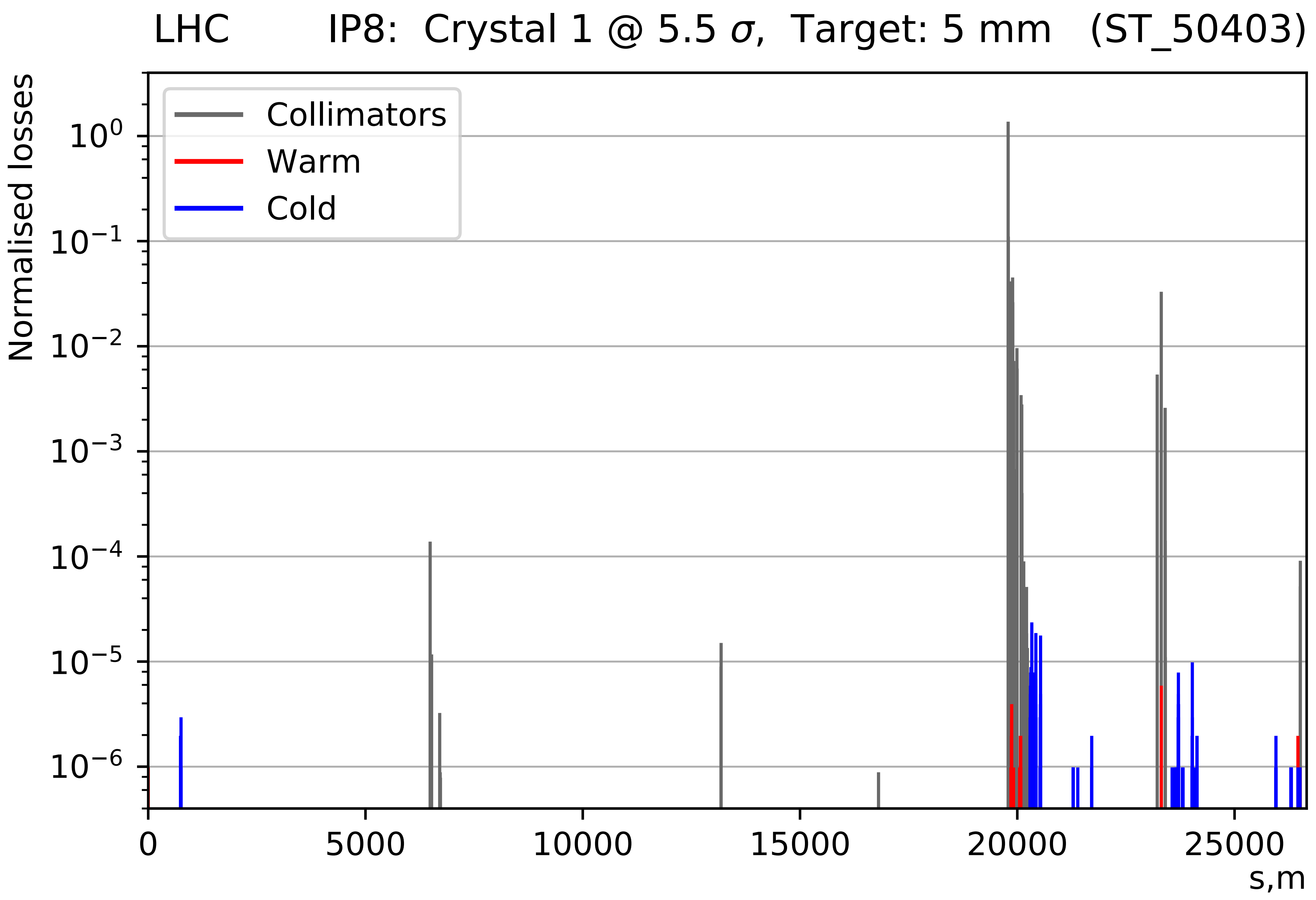
Advantages of the layout in IR3

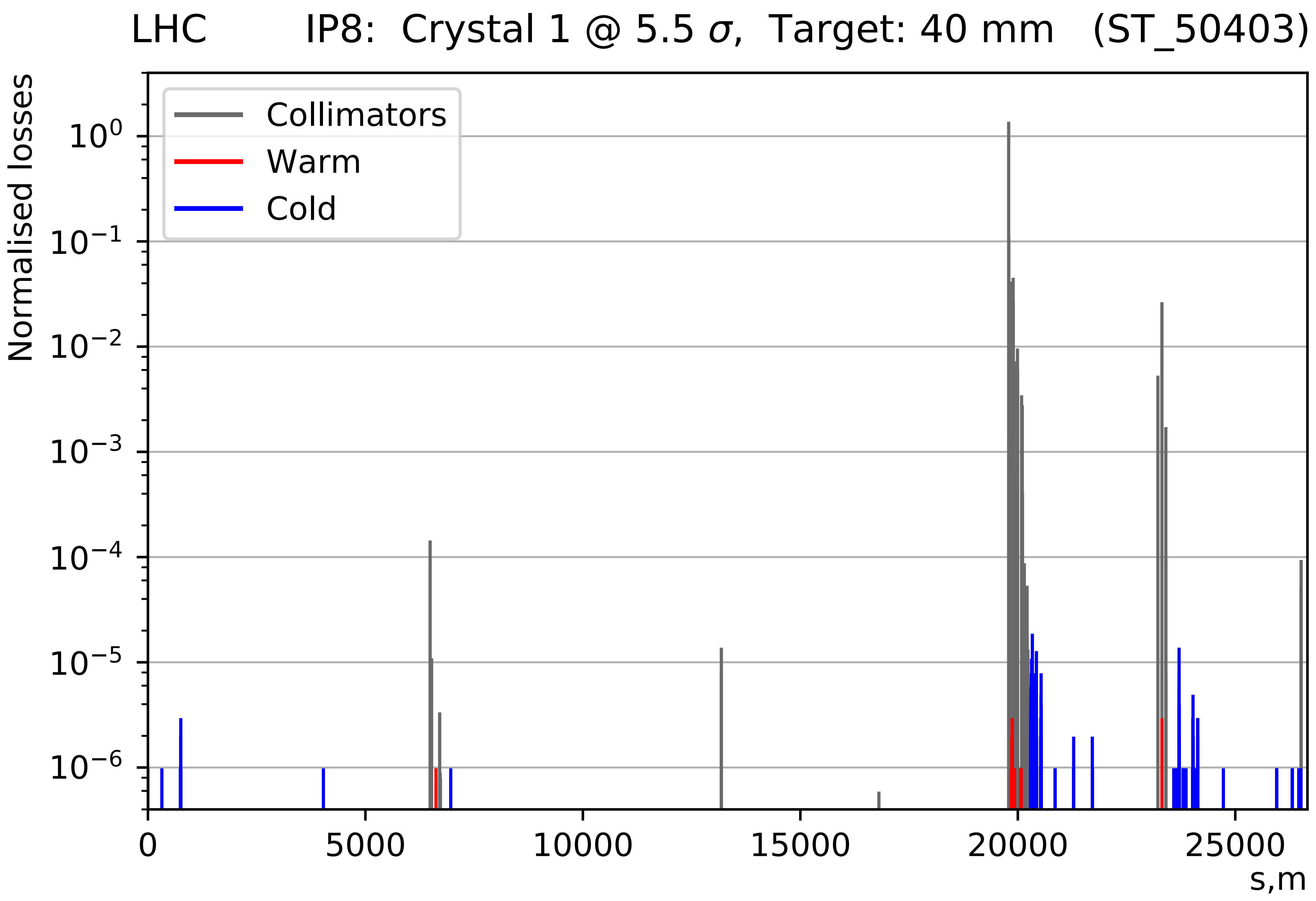
- Reduction of measurement time by a factor 5.2—5.7
- The detector in IR3 should be optimised for a harder spectra

Number of channeled Λc

T_{targ}	0.5 cm	2 cm	4 cm	4 cm / 0.5 cm
IR3	50 000 -66%	149 000	202 000 +36%	4.0
IR8	3 500 -63%	9 500	11 700 +23%	3.3
t8 / t3	4.7	5.2	5.7	

Longer Target, 5mm → 40mm: Loss maps

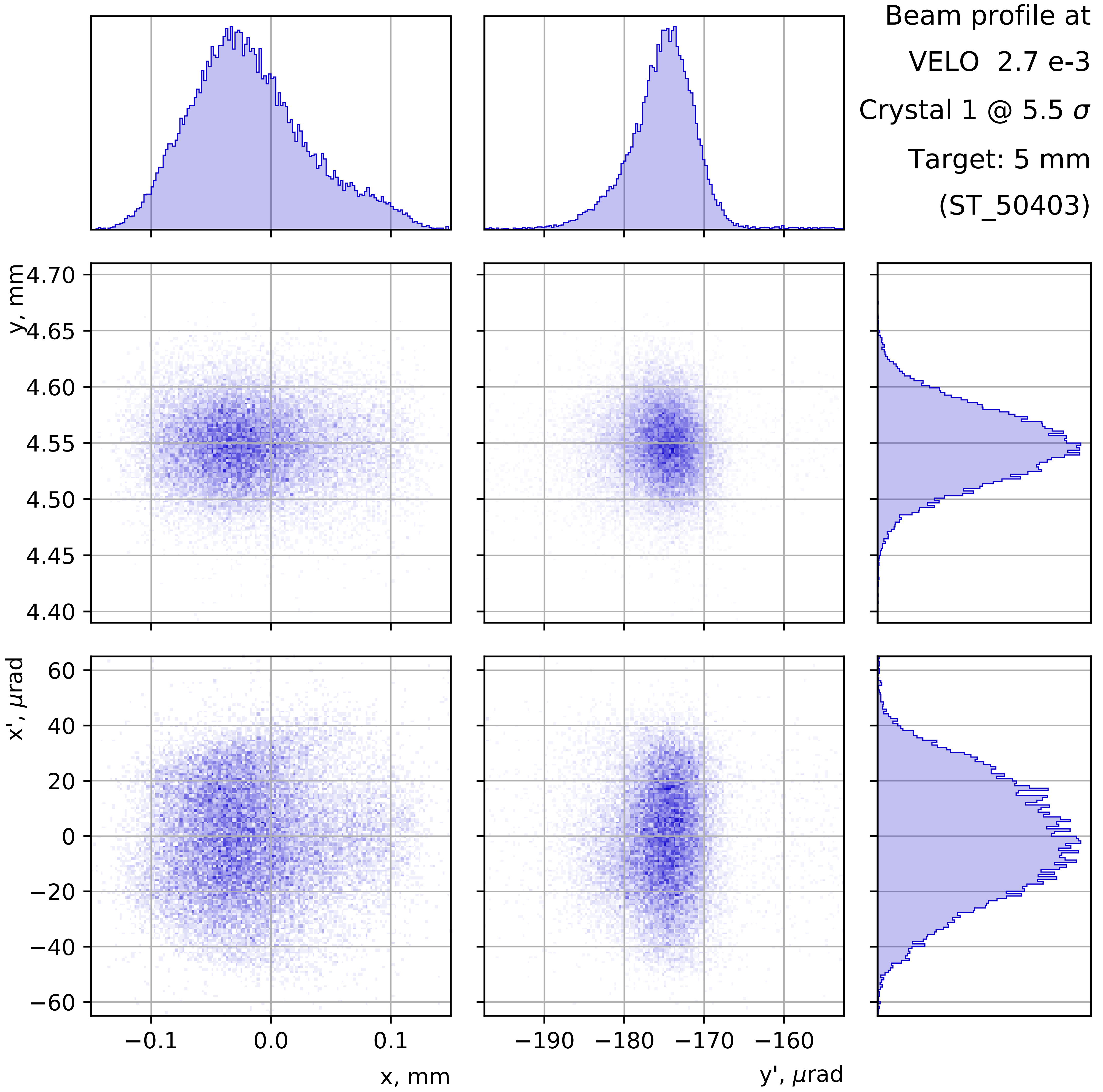




- SixTrack simulation of double crystal setup at IP8 with Crystal 1 @ 5.5 σ, Target length 5mm and 40mm
- Aperture losses in cold areas of IP8 are at the level of reference losses in IP7 (we are at the edge)
- Should be checked with complete energy deposition studies

Longer Target, 5mm → 40mm: deflected beam profile at VELO

Max. flux of protons at VELO: ~1.5x10^6 p/s (~1.5x10^9 p/s for 10s)



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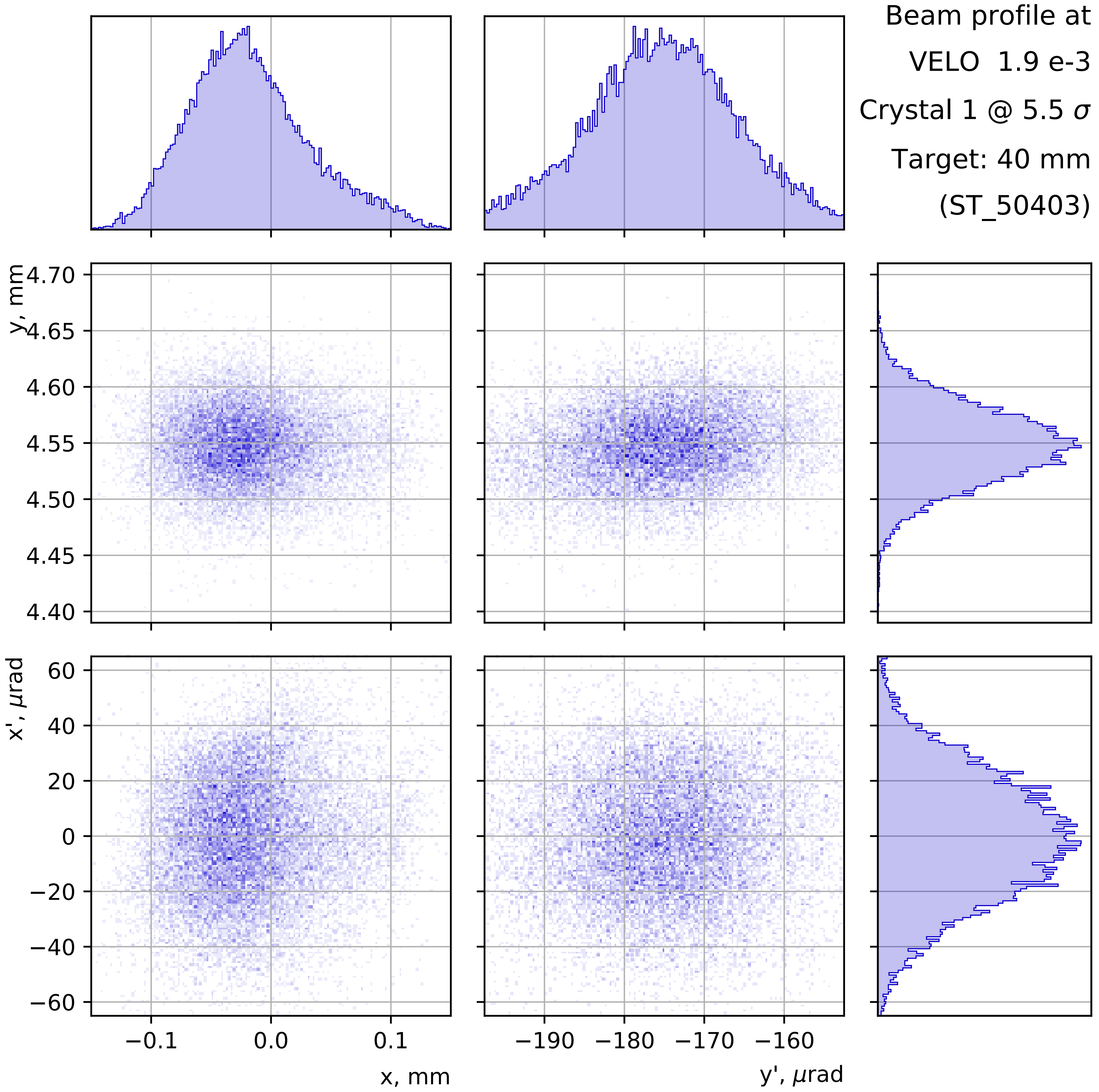
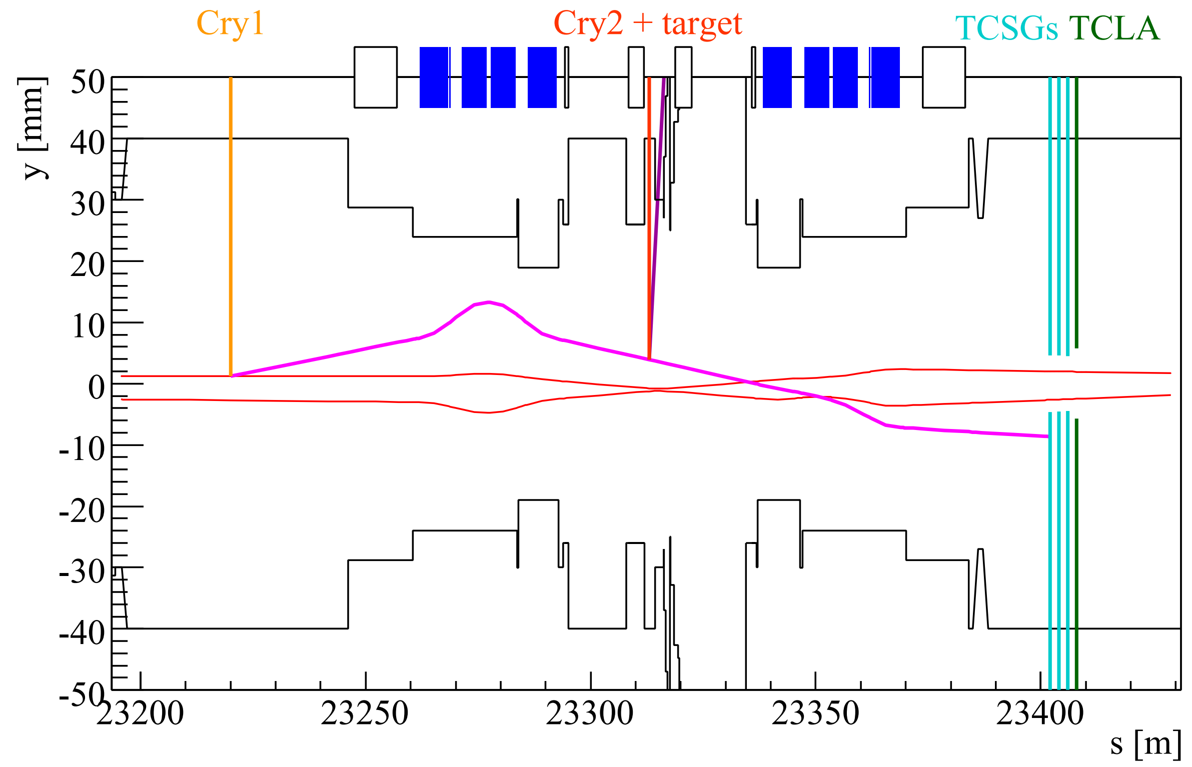
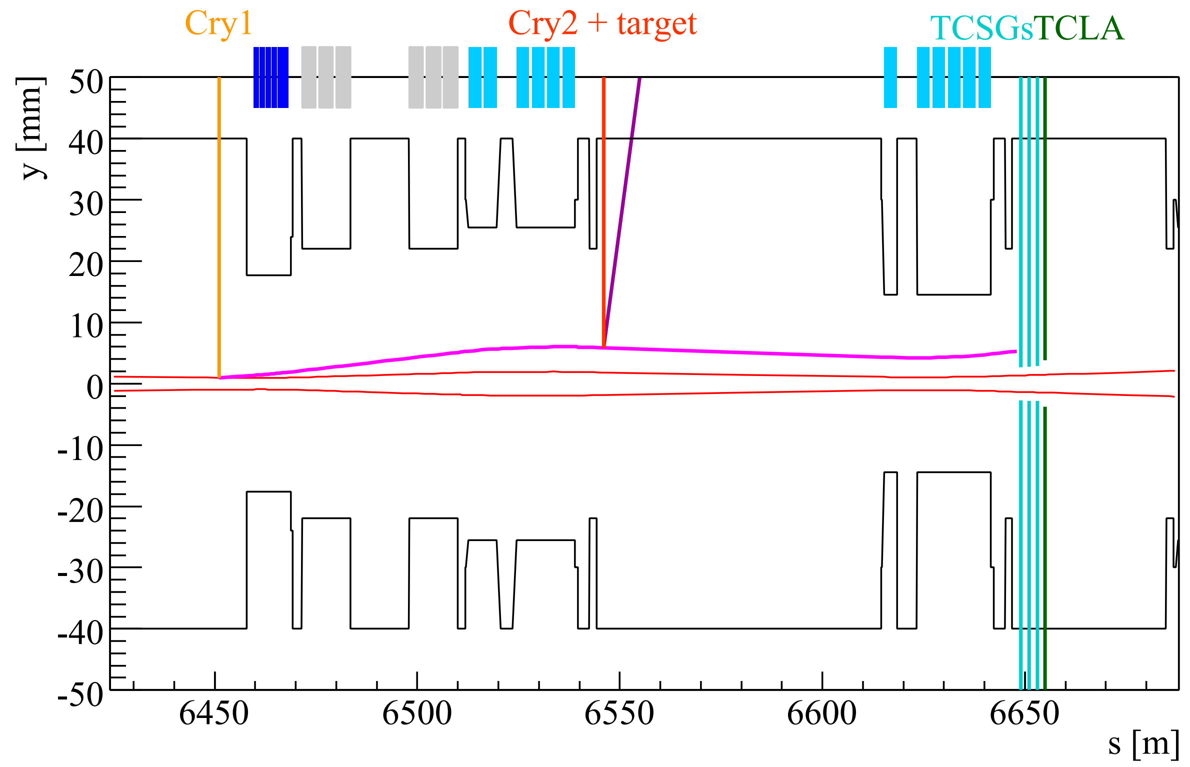


Conclusions and Outlook

Two proposed double crystal layouts: at IR8 (LHCb) and at IR3

- running experiment with 0.5 σ retraction of Crystal 1 w.r.t. TCP
  → 4.3×10^{10} (IR8) and 3.0×10^{10} (IR3) POT/fill
- IR3: advantage in Λc production, two beam pipes, no detector



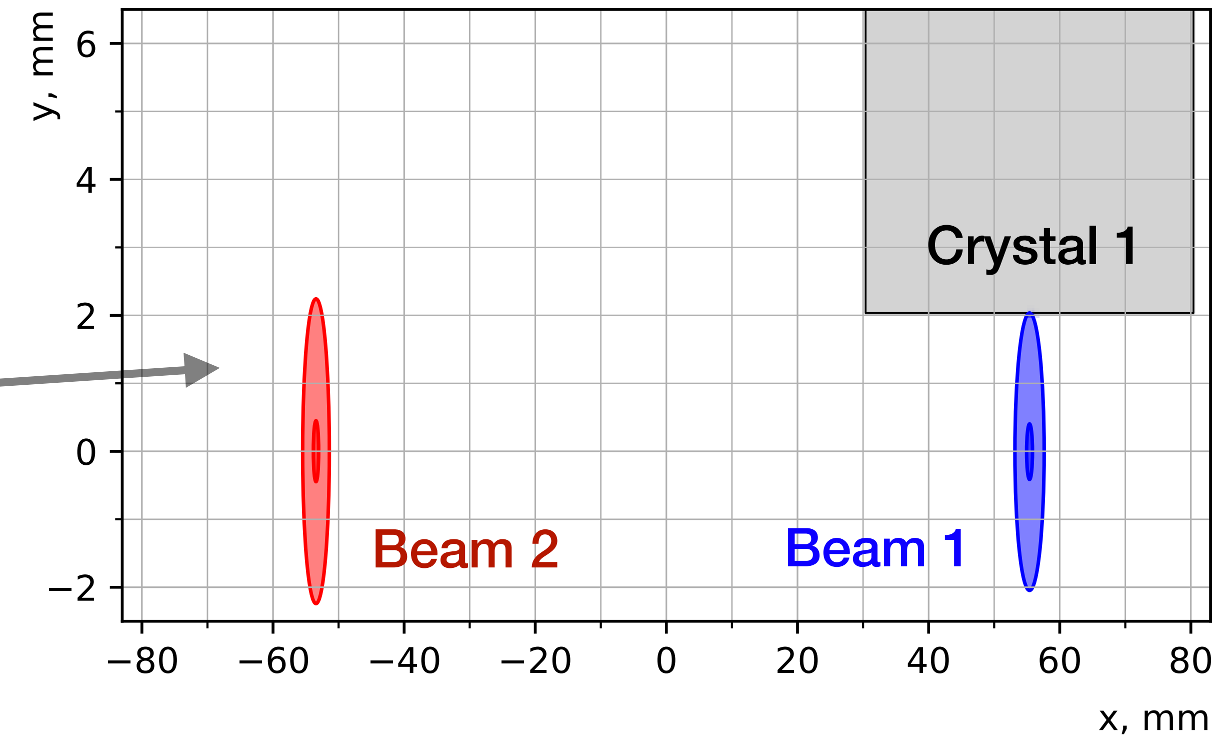


Beam and channeled halo displacements during levelling

- Beam 1 displacement at Crystal 1 (~0.15σ) → should be taken into account
- possible changes of optics for Run III and Run IV → additional check

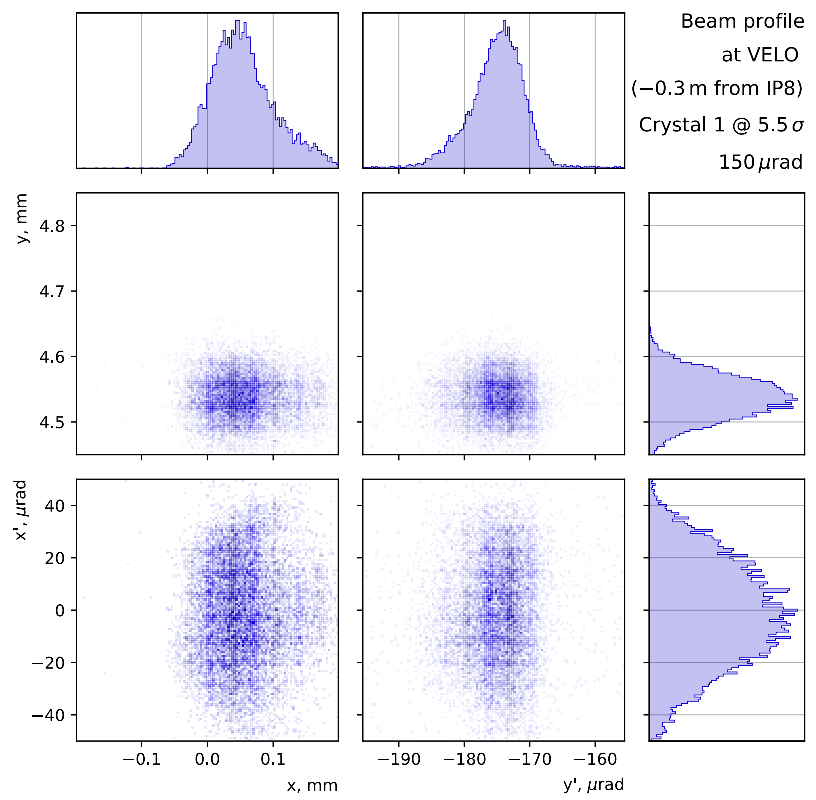
Space occupancy in the common region for the two beams (for IP8) is tight

- input for design of the crystal support/holder



Channeled halo and new VELO aperture

- no additional losses during the normal operation
- channeled halo does not hit the new VELO aperture (preliminary result)



Possible improvements of double crystal setup efficiency

- alternative layout (IR8→IR3) → ~ 7.5 times reduction in data taking time
- longer target (5→40mm) → ~ 6 times reduction in data taking time
- impact on the machine is tolerable, but at the edge (preliminary results)

Thank you